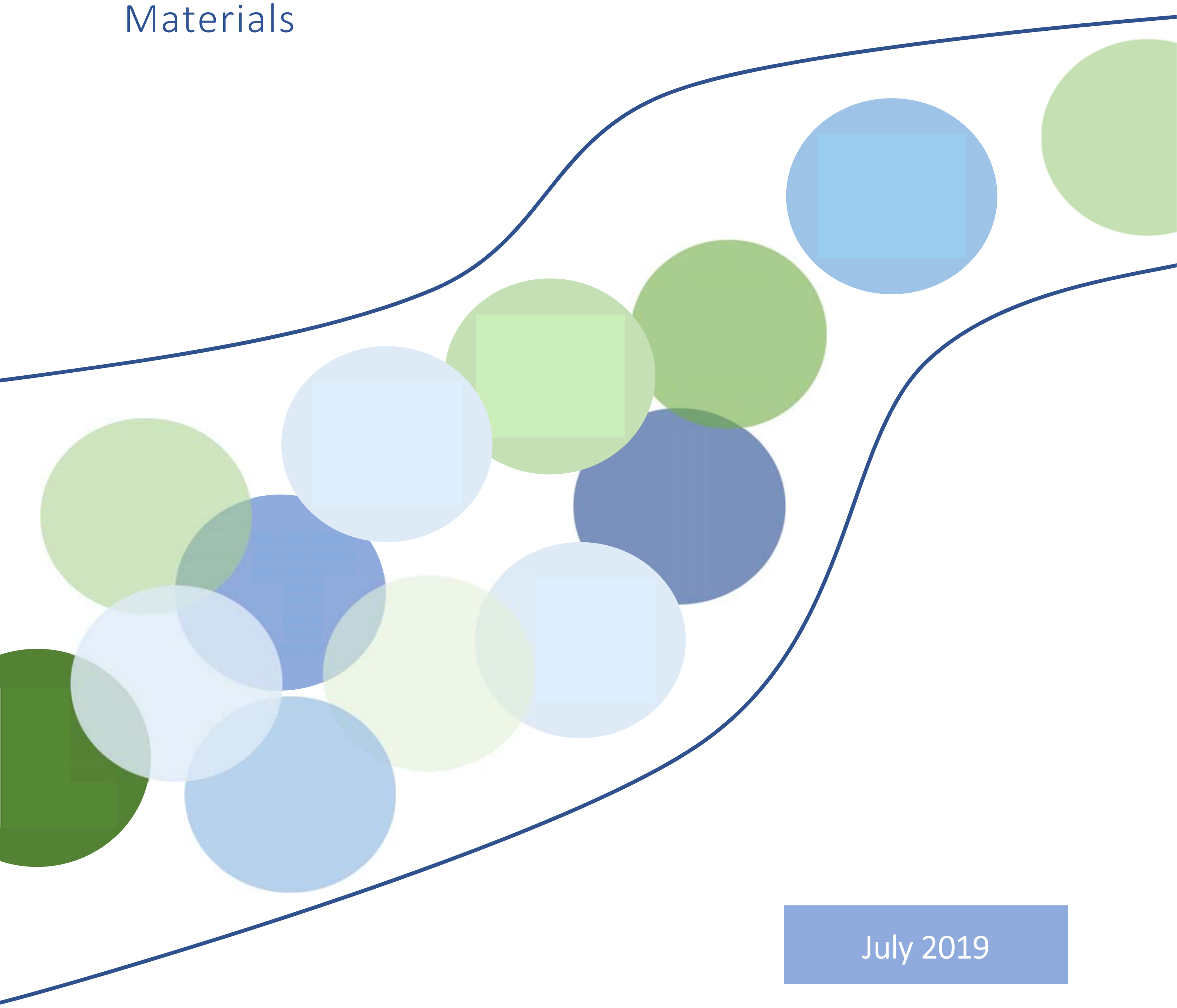
Deliverable 5.3

Life Cycle Assessment and Demand for Critical Materials



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About this report

This report describes the execution, results, and insights from Task 5.3 of the REEEM project, which analyses pathways towards a low-carbon energy system for the European Union. Part I of this document describes the LCA model developed as part of the Task and its application to the pathways to quantify the associated environmental impacts. Part II focuses on the critical materials assessment component of the Task and discusses how European energy technology related demand for these materials might change between the pathways explored in REEEM and assesses the risk of supply bottlenecks that might impede these technological transitions.

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About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

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Summary

This report describes the execution, results, and insights from Task 5.3 “Life Cycle Assessment for energy systems and demand for critical materials” of the REEEM project, which analyses pathways towards a low-carbon energy system for the European Union. The report consists of two parts:

- Part I, Life Cycle Assessment Study, describes the Life Cycle Assessment model that was developed during the project and its application to the REEEM pathways to quantify the associated environmental impacts.
- Part II, Critical Materials Assessment, focuses on the critical materials assessment and discusses how European energy technology related demand for these materials might change between the pathways explored in REEEM and assesses the risk of supply bottlenecks that might impede these technological transitions.

The application of the LCA model on two out of three REEEM pathways (i.e. Coalitions for a Low Carbon Path and Paris Agreement) in the Life Cycle Assessment Study showed that the reduction of climate change impacts differs from the reduction of GHG emissions embedded in the pathway narratives. This was mainly explained by (i) differences in scoping, with the narratives mainly focusing on EU28 geographical boundaries (although Paris Agreement Pathway also includes a wider perspective) while the study included the full life cycle of the energy systems (hence a global scope), (ii) limitations in the LCA model, which does not include time differentiation in processes occurring outside the EU, meaning that emission intensities are assumed the same as in 2015, thus leading to potential overestimations of the GHG emissions outside EU.

Another finding of the assessment is that neither of the pathways seem to perform better than the other. Taking the total human health damages, they end up at the same level of decrease between 2015 and 2050. However, it must be noted that environmental trade-offs occur, with some environmental impact categories tending to decrease more in one pathway over another. Some environmental impacts tended to increase between 2015 and 2050, regardless of which pathway was considered (e.g. water scarcity). Overall, the general trends in the environmental impacts were observed to be increasingly driven by the transport sector, which contributed to approx. 46% of the human health damages in 2050 in both pathways.

The findings of the Life Cycle Assessment Study illustrate the importance of considering a full life cycle perspective when assessing energy systems, and not just considering their operations and/or the related activities within the EU region. Such systemic and broad scoping is the only way to avoid environment burden-shifting from occurring. Likewise, it is as important to include a large spectrum of environmental problems to provide a complete overview of which environmental problems are predominant in the total environmental burden, where potential environmental trade-offs and burden shifting from one impact to another arise and which ones to prioritize in decision-making processes. A main recommendation is therefore to include such a holistic perspective when assessing energy systems to enable provision of reliable and unbiased support to policymakers.

Finally, Critical Materials Assessment found that all three REEEM pathways see their material demands dominated by electric and hybrid road transport vehicle technologies. Several potential supply bottlenecks exist across the geological, economic and geopolitical dimensions. The most at risk materials are cobalt and tellurium, with a second grouping being platinum, rare earths (particularly dysprosium and neodymium), gallium, and indium. In absolute terms, the Local Solutions pathway appears to have the highest cumulative materials demand and is therefore at the greatest risk of being affected by supply bottlenecks, while material demands for the Coalitions for a Low Carbon Path and Paris Agreement pathways are much lower. Key mitigation options for the EU are material efficiency, recycling and substitution, which should be considered as policy imperatives under all three pathways. A large fraction of the critical material demand assessed in this report arises from the transition to electro-mobility, so per unit estimates of material demand for vehicles are a key driver of the findings.

PART I: LIFE CYCLE ASSESSMENT STUDY

Introduction

The primary goal of the REEEM project is to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of the transition to a competitive low-carbon European Union (EU) society. In the EU, the entire energy system, which encompasses electricity and heat supply (incl. cooling as well) and transportation support, contributes 80% to the total greenhouse gas emissions. Energy system investment decisions can significantly impact the environment and the transition to a more environmentally sustainable society. Environment here should be understood in a broad sense, not just addressing climate change impacts from greenhouse gases (which can be reflected by the change in radiative forcing – expressed in kg-CO2 equivalent – or by metrics that model further the cause-effect chain and capture the potential damages to human health and ecosystems) but other types of environmental problems like chemical pollution, resource depletion, etc. To ensure environmental sustainability, it is important to quantify to what extent the anticipated pathways towards a low-carbon EU society contribute to all those environmental problems, and whether they lead to actual impact reductions.

To conduct such quantification, life cycle assessment (LCA) can be conducted. LCA is an ISO-standardised methodology that enables us to quantify a large variety of environmental impacts in a life cycle perspective, i.e. from extraction of raw materials, through production and use, up to end-of-life and potential recycling or disposal (Laurent et al. 2018). Thanks to its holistic nature, LCA is widely used to address eco-efficiency questions in comparative studies; for example addressing whether a specific technology is better than another, providing the same service. The inclusion of the full life cycle perspective and the broad variety of environmental problems is essential to identify potential hotspots, which are places in the energy system life cycle that are associated with large environment impacts, and potential burden-shifting across life cycle stages or environmental problems. An example of environmental burden-shifting could occur if a particular strategy leads to decreasing of some environmental impacts (e.g. climate change impacts from greenhouse gases) while increasing others at the same time (e.g. chemical pollution) (Laurent and Espinosa 2015).

LCA has traditionally been applied to products or specific technologies, and its use for larger assessment (e.g. organisations or systems at urban, regional or country scales) are recent. Such a "large-scale assessment" adds much complexity because of the modelling of entire systems, which are composed of several interacting elements (e.g. technologies, sectors, etc.). They also require some adaptation in the steps of the LCA methodology, e.g. functional unit (see Structure of the model).

Task 5.3 included the building and application of an LCA model, as specified in the task description – see below.

Task description (specific to LCA part):
Environmental assessment of energy technologies will be performed, informed by the other tasks within this WP and following the EU ILCD Handbook for the application of LCA released in 2010. The

results will serve to characterise the environmental sustainability of the systems and provide recommendations to energy policy makers. Life cycle inventories (LCIs) of different energy technologies will be modelled, building on inputs from WP6, in particular Task 6.2, combined with recent developments in LCI knowledge, e.g., via the release of the spatially differentiated Ecoinvent 3.1.

In Task 5.3, an LCA model has thus been developed to enable the assessment of the entire energy systems of EU with a full life cycle coverage and with a coverage of several environmental impact categories (see Structure of the model). Three pathways are considered in REEEM; Coalitions for a low carbon path, Local solutions, and Paris Agreement. The first, in this report referred to as the Base Pathway, achieves an 80% reduction in energy-related emissions by 2050 as compared to 1990 levels. The second also achieves an 80% reduction, but with a significant fraction of the climate mitigation efforts driven by communities and individuals. The third achieves a 95% reduction corresponding to the obligations agreed upon in the Paris Agreement. For more details on the full narrative of the pathways see D1.2b Integrated Report on Impact Assessment. The LCA model was applied to all energy systems of the Base Pathway and the Paris Agreement Pathways; the Local Solutions Pathway was not assessed due to time constraints (the provision of outputs from TIMES model, which are used as inputs to the LCA model, was significantly delayed). TIMES is an energy system model generator using a bottom-up linear optimization model (REEEM, 2019). Here, the Pan-European TIMES model, which covers the EU-28 countries, with the addition of Norway and Switzerland, is used. Only assessment at full EU-28 scale was assessed since the TIMES model in REEEM was developed to fit EU-wide narratives and it therefore does not bring full consistency at national level. For example, national energy policies are not factored in the TIMES model, meaning that potentially major discrepancies exist between national pathways framed in existing and planned policies and national trends resulting from the TIMES model. The assessments and the reporting of the LCA model and application have been conducted, following the ISO14044 standards (2006) and the EU Commission's ILCD Handbook (European Commission - Joint Research Centre 2010), which provides detailed technical guidance for LCA application.

The subsequent sections are loosely structured on the concise format of a scientific article. The model structure is first briefly introduced, before the description of the LCA and its underlying methodological steps, including the detailed model development, are described for performing the LCA of energy systems for any given pathway. The results from its application to EU28 for the two tested pathways are thereafter addressed followed by the conclusions and recommendations derived hereof. The core of the report is complemented by large appendices to ensure full transparency and reproducibility of the developed model (Appendices A-B).

Structure of the model

The outputs of the TIMES PanEU model (developed by the University of Stuttgart in REEEM) are used as inputs for constructing the LCA model that strongly relies on life cycle inventories – see Figure 1. Life cycle inventories (LCI) are building bricks for the model that compiles all inputs (energy, intermediate materials or products, resources) and outputs (energy, waste, emissions, intermediate products) of a given process or activity (e.g. rolled steel production, high-voltage electricity from a specific technology of coal-fired power plant in a given country, etc.). They can be regarded as mini-life cycle assessment of a given process or activity, although some may not cover the entire life cycle of the product or activity (e.g. steel production process does not include the disposal of the steel after usage).

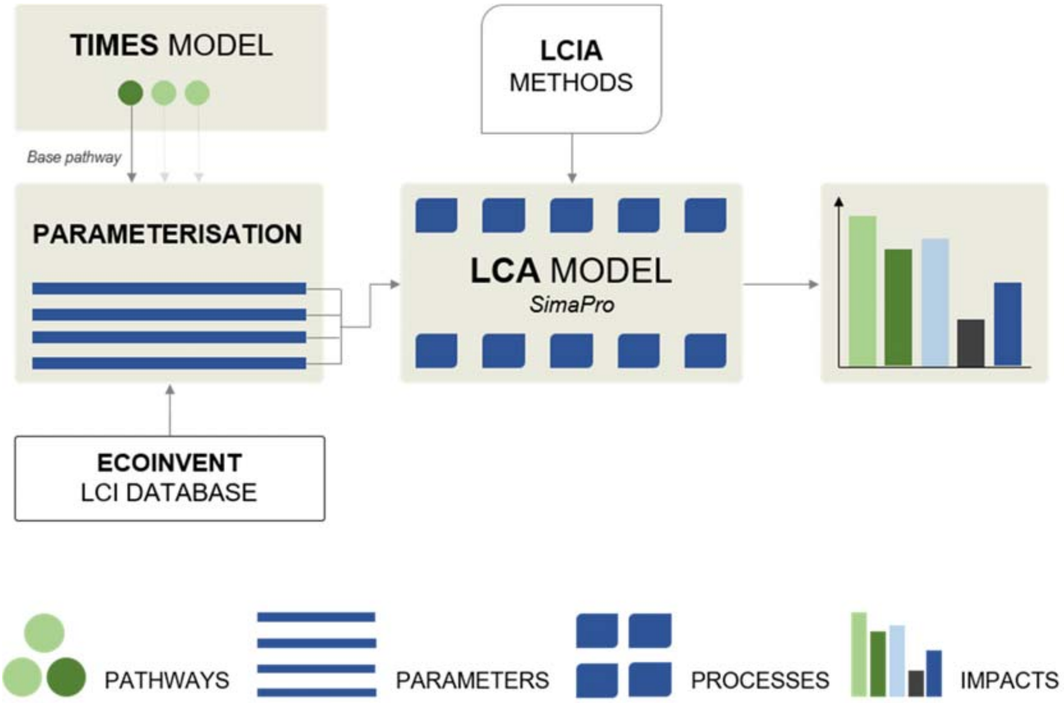

Figure 1. Illustration of the structure and connections of the LCA model with TIMES PanEU model

Default LCI were built for each technology modelled under the TIMES PanEU model used in REEEM, starting, wherever possible, from existing LCI data from the spatially-differentiated ecoinvent 3.3 database, which the largest existing LCI database on the market (> 20,000 LCI processes/activities; not that the data are licensed and hence cannot be publicly shared/released). These existing LCI data were modified to match the technological, geographical and temporal scopes of the energy system in REEEM. Concretely, it means that these LCIs were parameterized (see Fig. 1) to account for technological, spatial and temporal specificities (e.g. outputs from TIMES PanEU model were used to support information on evolution of efficiencies over time and across countries, etc.). When the technology was not available in ecoinvent 3.3 (Wernet et al. 2016), LCIs were built from scratch with data from scientific literature sources.

To accommodate this needed differentiation of the model in technology, time and space, and to enable the assessment of several pathways, the parameterization was performed in Microsoft Excel and linked to LCA software SimaPro (PRé 2019) using one of its features (available in Developer license). The Excel model uses a table input mirroring the Excel table output from TIMES PanEU and then computes those inputs with other parameters to build an interface of 33,112 external links to the LCI used in the SimaPro model. Every parameter that changes from one pathway, country, year or technology to another is defined as a variable in the Excel model. To build the inventories in the SimaPro model, we used data from the TIMES PanEU model on final energy and primary energy consumption, installed capacity, electricity and heat production, fuel input for heat and electricity production, vehicle stock, vehicle activity and fuel input for transportation for each country individually. In total, the resulting SimaPro model includes 7,275 created and edited processes (234 specific for each country; 233 for EU28 as no electricity import processes is required, 19 background processes such as stoves, and three for European electricity mix), in addition to the already existing processes/activities present in ecoinvent 3.3 default database. The modelling of each category of energy systems (electricity, heat and transportation) is described in Section LCA methodology (with detailed documentation in Appendix B). The LCA model is finally complemented with an environmental impact assessment module, which comprises the life cycle impact assessment (LCIA) methods used to translate the LCI into potential impacts on the environment (see Figure 1). These LCIA methods cover a wide range of environmental problems, which can thus be quantified. Further details on the selection and specificities of these methods are provided in Section LCA methodology.

LCA methodology

The LCA in this study was carried out by following the overall guidelines of ISO 14044:2006 (2006) and the ILCD Handbook guidance by the EU Commission (European Commission - Joint Research Centre 2010). In the following subsections, a description of the different methodological steps and modelling processes is provided, first describing the goal and scope definition of the LCA, followed by a summary of how the system model and its LCI were built (complemented with full documentation in Appendix B), and finally a brief description of the impact assessment step is provided.

Defining the goal and scope of the assessment

The main goal of the LCA is to assess the potential environmental impacts of the pathways defined in REEEM, to identify potential environmental hotspots and/or burden-shifting as well as evaluating the comparative performances of the EU28 pathways relative to the CO2 emission reduction targets when considering a full life cycle perspective.

To ensure a fair comparison between the pathways considered, a functional unit[1] needs to be defined (2006; European Commission - Joint Research Centre 2010). With consideration to the large-scale and time-dependent scoping of the assessment, adjustments were brought to the conventional way of defining and quantifying the functional units, as recommended in Laurent et al. (2018). The functional unit was thus defined as the "meeting of the annual energy demand of the EU28 countries between 2015 and 2050", where energy demand is characterized by the energy needed for electricity, heating (including cooling) and transportation. The demand is divided between five sectors (default output from TIMES PanEU model): agriculture, commercial, households, industry and transportation. In the assessments, the three categories of energy systems are considered in a large-scale perspective (i.e. national level) and the focus is on future developments with analyses carried out for one year every fifth year from 2015 to 2050.

Given the large-scale scope of the study, a consequential modelling[2] approach was adopted, with use of system expansion to address multi-functionality of the processes (as recommended by ISO 14044 and ILCD Handbook). For example, recycling of materials and use of byproducts such as slags were handled by modelling avoidance of virgin materials production and processing. The only exception hereof, is for heat from co-generated heat and power plants, where the energy for heat is separated from the energy for electricity by allocation based on energy content. The study considers all life cycle stages of the energy systems from cradle to grave, and includes both the life cycles of the energy system infrastructures (e.g. the power plant) and those of the fuels, the latter being relevant for all non-renewable fuel sources. Figure 2 illustrates the system boundaries of the LCA. It should be noted that the full life cycle perspective adopted in the system boundaries of the LCA model does not match the system boundaries of the TIMES PanEU model in REEEM, which is geographically-delimited. It means that the CO2 emissions in the TIMES

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[1] A functional unit defines the qualitative aspects and quantifies the quantitative aspects of the function to ensure a fair and relevant comparison of alternative ways of providing a function (Bjørn et al. 2018).

[2] In consequential modelling the overall aim is to describe the changes (i.e. consequences) to the economy (and thereby the environment) caused by the introduction of the studied system (Bjørn et al. 2018).

model do not account for CO2 emissions occurring outside Europe and are therefore lower, compared to those obtained with a full life cycle perspective (like in this assessment).

Only the entire EU28 region was assessed. The TIMES PanEU model is indeed built on assumptions made at EU level and relies on cost optimization to produce least-cost energy systems. Therefore, it does not consider national energy policies. This means that important discrepancies may exist between the actual pathways defined by policies and regulatory engagements of individual European countries and the pathways issued from the TIMES model in REEEM. This is the reason why no national assessment was performed herein.

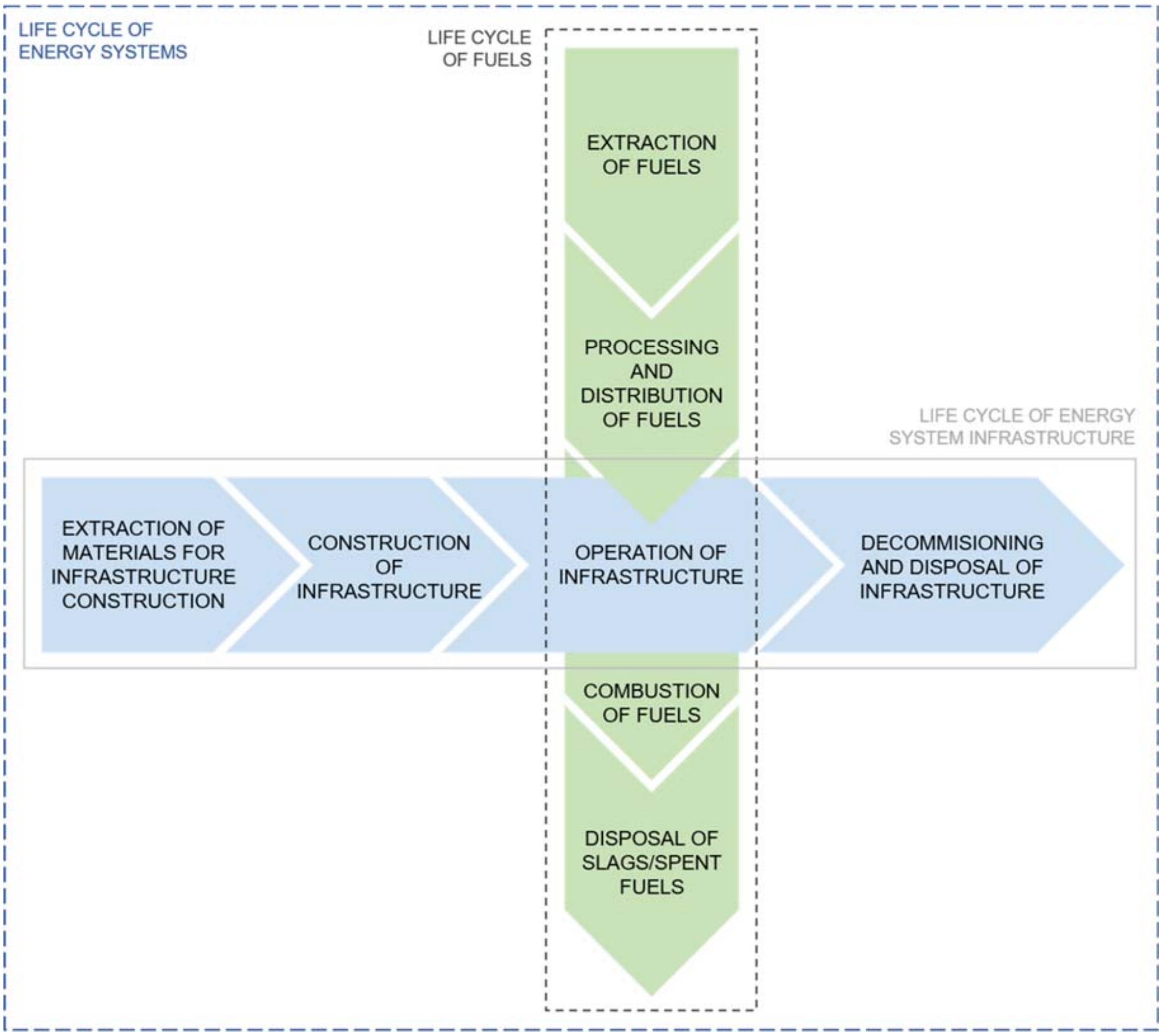

Figure 2. Generic system boundaries of all systems considered in the assessment. Each specific technology or system can be represented with above life cycles and were modeled as such.

Inventory building

As previously mentioned, the inventory was modelled with inputs from the TIMES PanEU model. In the following subsections a general description of the process structure for each type of energy systems (electricity, heating and transportation) is given.

Process structure for electricity

Since all technological types of combustion plants (i.e. hard coal, lignite, oil, natural gas, biomass, non-renewable/industrial waste, and biogas), nuclear plants and hydrogen fuel cell plants were modelled in a similar way, only a modelling description for hard coal plants is provided hereafter for illustrative purposes. Detailed model descriptions of the other energy sources and technologies are available in Appendix B.

Six different technologies for electricity production from hard coal combustion is provided as output from the TIMES PanEU model:

- **Steam turbine**
- **Steam turbine, CCS Retrofit (CCS: Carbon Capture and Storage)**
- **Steam turbine, CO2 Sequestration Post Combustion**
- **Steam turbine, CO2 Sequestration Oxyfuel**
- **IGCC (Integrated gasification combined cycle)**
- **IGCC, CO2 Sequestration**

A template process “Electricity production, hard coal, steam turbine” was constructed based on the process ”Electricity production, hard coal” available in ecoinvent v.3.3. The process was built so that all the inputs and outputs (incl. resource consumption, emissions) are proportional to the country average efficiency of the power plants. The structure of the process can be seen in Table 1. It was considered as a “base process” for modelling the other technology types. The base process was thus adapted and the additional technologies, e.g. carbon capture, were added to build the remaining five technologies. A thorough description of how the processes for all types of plants were modelled can be found in Appendix B.

Table 1. Structure of the “Electricity production, hard coal” in ecoinvent v.3.3.

Process/substance	**Type**
1 kWh of electricity	*Output to technosphere*
Power plant (construction)	Input from technosphere
Hard coal	Input from technosphere
Light fuel oil	Input from technosphere
Water for cooling	Input from nature
Water, decarbonised	Input from technosphere
Water, softened	Input from technosphere
Chlorine	Input from technosphere
DeNOx technologies (for X kg of NOx retained / kWh)	Input from technosphere
DeSOx technologies (for X kg of SOx retained / kWh)	Input from technosphere

Various substances	Emissions to the air
Water	Emissions to water
Residue from cooling tower	Waste to treatment
Ashes	Waste to treatment

The flows of each inputs/outputs (e.g. energy, materials, resources, emissions, waste, etc.) in the ecoinvent process, except Hard coal consumption (see Eq. 4 for details), was determined as follows:

$$Flow_{process\ x} = Factor_{MJ\ kWh} * C_{1x} \quad (1)$$

Where C_1 is a coefficient obtained from the documentation embedded in ecoinvent database (specific documentation for each LCI process), and $Factor_{MJ\ kWh}$ is defined as:

$$Factor_{MJ\ kWh} = {}^{3.6}/_{\eta} \quad (2)$$

Where η is the country average efficiency of the power plants (retrieved from ecoinvent documentation), and is thus defined per country and change over time. From this, the global flows were defined as:

$$Flow_{process\ x} = {}^{3.6}/_{\eta} * C_{1x} = {}^{C_{2x}}/_{\eta} \quad (3)$$

Where C_2 is the aggregated emission coefficient used in the LCA model.

The flow of Hard coal consumption was determined as follows:

$$Flow_{hard\ coal} = \frac{3.6}{LHV * \eta} \quad (4)$$

With values of η (the average efficiency) and $Flow_{hard\ coal}$ retrieved from ecoinvent documentation. The average lower heating value (LHV) of hard coal used in each country could thereby be determined. LHV was assumed constant until 2050. The average efficiency of country C in year Y was given by the TIMES PanEU outputs, and was determined by dividing the output electricity by the input of fuel:

$$\eta_{c\ y} = \frac{Electricity\ Production\ Public\ and\ Industrial\ Power\ Plant, country\ c, year\ y\ [kWh]}{Fuel\ input\ Public\ and\ Industrial\ Power\ Plant, country\ c, year\ y\ [kWh]} \quad (5)$$

We thus obtained the hard coal consumption for each country, each year.

All other flows were extracted from ecoinvent documentation specific to each process. In Appendix B, additional information on the flows for the other processes than electricity production from coal can be found. For countries that did not have a process already existing in ecoinvent, a process was built using the geometric mean of the coefficients of the countries that had existing processes in ecoinvent. This allowed to determine all the coefficients for "Electricity production, hard coal" for each country in the EU28. Coefficients were assumed constant until 2050, which may be a limitation in the model (further implementation of time differentiation could be explored in future works). By dividing the coefficients for all other flows by the efficiency for each year and each country, the remaining flows can be obtained.

Heating

Table B6 in Appendix B shows the list of CHP plants (as given by TIMES PanEU) and the approach used to model each of them. Energy allocation was performed to obtain two separated processes, one for heat production and one for electricity production, from the same CHP plant. Whenever a suitable cogeneration process was available in ecoinvent the allocation-based dataset of that process was chosen (replacing the single inputs/outputs with consequential-based unit processes). When no process was available, copies of the closest technology, either CHP or a conventional electricity power plants, were selected, following what was done for the conventional electricity generation power plants (as described in section Process structure for electricity). In the cases where a copy of the conventional power plant technology was taken, energy allocation was performed.

Therefore, for heat generation, new flows for a certain input (or output) *x* were calculated as:

$$Flow_x = \frac{C_{2,x}}{3.6\frac{MJ}{kWh}} * \frac{eff_{heat}}{eff_{tot}} \quad (6)$$

where eff_{heat} is the heat efficiency and eff_{tot} is the total efficiency of the CHP plant. In this way, the flow was also rescaled to the output of 1 MJ heat.

In contrast, for electricity generation, the flow was calculated as:

$$Flow_x = C_{2,x} * \frac{eff_{electric}}{eff_{tot}} \quad (7)$$

where $eff_{electric}$ is the electricity efficiency.

To calculate heat and electricity efficiencies the following respective formulas were used from (Energinet.dk and Danish Energy Agency 2012):

$$\eta_{e,MC} = \eta_{e,c} * \left\{1 - \frac{c_v}{c_b + c_v} * \frac{Q_{MC}}{Q_B}\right\} \quad (8)$$

$$\eta_{q,MC} = \frac{\eta_{e,c}}{c_b + c_v} * \frac{Q_{MC}}{Q_B} \quad (9)$$

for heat efficiency; where:
$\eta_{e,MC}$: electric efficiency at minimum low-pressure condensation;
$\eta_{q,MC}$: heat efficiency at minimum low-pressure condensation;
$\eta_{e,c}$: electricity efficiency in full condensation mode;
c_v: Loss of electricity generation per unit of heat generated at fixed fuel input; assumed constant;
c_b: Back-pressure coefficient (electricity divided by heat); assumed constant;
Q_{MC}: Heat capacity at minimum low-pressure condensation;
Q_B: Heat capacity in full back-pressure mode (no low-pressure condensation)

All parameters were extracted from (Energinet.dk and Danish Energy Agency 2012). The formulas enabled us to calculate the efficiency at minimum low-pressure condensation, which is an operating condition of the plant between the full condensation mode (no heat use) and the back pressure mode (all heat is used for heating purposes) (Eurelectric 2002a).

Process structure for transportation

The model includes eight types of vehicles (cars, heavy duty vehicles, light duty vehicles, busses, motorcycles, rail, aviation and navigation). For each type of vehicles, the model has been parameterized for fuel consumption, vehicle weight, battery weight and fuel cell weight. Vehicle and battery weights vary depending on the type of vehicle, e.g. weight of an internal combustion engine vehicle (ICEV) is different from a hybrid electric vehicle (HEV), while the type of fuel does not vary. Fuel consumption per person and per km, i.e. pkm, (or per cargo mass per km, i.e. tkm) was obtained from TIMES PanEU data by dividing the total fuel input (MJ) by the total activity of the vehicle (pkm) and the LHV of the fuel (LHV of fuels are given in (Boundy et al. 2011) and (UN 2011)). The evolution in vehicle weight over time is calculated as demonstrated in Bohnes et al. (2017), by assuming a constant reduction of 1.2% until 2050 (Douglas and Stewart 2011).

It should be noted that the modelled technologies and their characteristics are the same for every country and only fuel consumption varies between countries. Furthermore, only an average medium size vehicle was modelled to represent the fleets, and no distinction was therefore made between small and large vehicles within the vehicle type.

When a vehicle has more than one type of fuel input in the TIMES PanEU model (e.g. biomass, petroleum-based fuels, etc.), it was modeled as a vehicle running on a blend of fuel types. Diesel or gasoline cars thus have the option of blending fuels. For biofuels and types of fuels that are not present in ecoinvent (i.e. DME; fossil FT diesel, fossil methanol and hydrogen) data on emissions from different types of vehicles and data on the fuel production process was retrieved from the GREET model (Argonne National Laboratory's Systems Assessment Group 2018). GREET provides emission factors in ton/MJ fuel, which are used to calculate coefficients (in kg emissions/kg fuel, using the same LHV used to calculate fuel consumption) which are then multiplied by the fuel consumption. GREET includes only those emissions that contribute to climate change impacts and nothing else, so the dataset is considered to be limited. Furthermore, the model does not specify to which compartment the emissions are emitted, thus it was assumed that all is emitted to air. When emissions inventories from GREET were used, it was assumed that the unspecified emissions in GREET refer to emissions to low populated areas, while urban emissions refer to emissions to high population areas (modeled as such in SimaPro).

In general, it was assumed that all emissions solely depend on the actual fuel consumption from TIMES PanEU (thus disregarding emission standards). However, the emissions from tyre and brake wear (TBW) were modelled as in the default ecoinvent LCI processes, as they do not depend on fuel use.

Sectors

The TIMES PanEU output files report five sectors: Industry, Commercial, Households, Agriculture and Transport. For each of these, the energy consumption is reported for energy carriers shown in Table 2, which also summarizes how the consumption of each energy carrier has been modelled in all sectors but transport. The transport sector is modelled differently from the other four sectors, because the TIMES output files include tables with detailed information on how the energy carriers are used in transport. Further documentation on the modelling of all sectors is available in Appendix B.

Table 2. Sector differentiation between energy carriers

Energy carrier	Agriculture	Commercial	Households	Industry
Coal	Heat production from hard coal briquettes (in 5-15 kW stove), central or small-scale.	Heat production from hard coal briquettes (in 5-15 kW stove), central or small-scale.	Heat production from hard coal briquettes (in 5-15 kW stove), central or small-scale.	Heat production from coal coke (in industrial 1-10 MW furnace), district or industrial.
Petroleum	Diesel burned in agricultural machinery.	-	-	-
Gas	Heat production from natural gas (in <100 kW low-NOx condensing non-modulating boiler)	Heat production from natural gas (in <100 kW low-NOx condensing non-modulating boiler) AND Natural gas burned in gas stove.	Heat production from natural gas (in <100 kW low-NOx condensing non-modulating boiler) AND Natural gas burned in gas stove.	Heat production from natural gas (in >100 kW industrial low-NOx furnace), district or industrial
Electricity	High, medium and low voltage	High, medium and low voltage	High, medium and low voltage	High, medium and low voltage
Heat	Heat mix	Heat mix	Heat mix	Heat mix
Renewables	-	-	-	-
Waste	Energy waste incineration	Energy waste incineration	Energy waste incineration	Energy waste incineration
Others	Renewables, DME, renewables, hydrogen and renewables, methanol	Renewables, DME, renewables, hydrogen and renewables, methanol	Renewables, DME, renewables, hydrogen and renewables, methanol	Renewables, DME, renewables, hydrogen and renewables, methanol
Stoves	---	---	Gas: Stove for natural gas & Electricity: Stove, electricity, burned in gas stove	---

Life cycle impact assessment

The impact assessment was performed using a number of available LCIA methods. Most up-to-date methods were used, relying on recent advances (e.g. Huijbregts et al. 2017). The selected LCIA methods cover all commonly assessed environmental impact categories in LCA studies (with relevance to energy systems). These are reported in Table 3.

In the present report, impact assessment results are only provided for a selection of environmental impact indicators. Detailed results are available in Appendix C for all impacts.

Table 3. Environmental impact categories included in the assessment.[a]

Impact category	LCIA method [Ref]	Impact score unit
Climate change	Huijbregts et al. 2017 (based on IPCC AR5)	kg CO_2-eq
Stratospheric ozone depletion	Huijbregts et al. 2017	kg CFC11-eq
Terrestrial acidification	Huijbregts et al. 2017	kg SO_2-eq
Photochemical ozone formation (impacting human health)	Huijbregts et al. 2017	kg NO_x-eq
Freshwater eutrophication	Huijbregts et al. 2017	kg P-eq to freshwater
Marine eutrophication	Huijbregts et al. 2017	kg N-eq to marine water
Ionizing radiation	Huijbregts et al. 2017	kBq Co-60 to air eq
Particulate matter formation	Huijbregts et al. 2017	Disability-adjusted life years (DALY)
Human toxicity, cancer and non-cancer effects (i.e. toxic impacts of chemicals releases on human health)	Hauschild et al. 2008; Rosenbaum et al. 2008	cases (of cancer or non-cancer effects)
Freshwater toxicity (i.e. toxic impacts of chemicals releases on freshwater ecosystems)	Hauschild et al. 2008; Rosenbaum et al. 2008	Potentially affected fraction of species (PAF).m3.d
Land use	Huijbregts et al. 2017	species. yr
Water use	Pfister et al. 2009	m3
Mineral, metal and fossils depletion	Hauschild et al. 2013	Kg-Sb-eq
Human health damages [b]	Huijbregts et al. 2017	Disability-Adjusted Life Years (DALY)

[a] Other LCIA methods were also tested as sensitivity analysis (data not shown).

[b] Contribution from the following impact categories: climate change, stratospheric ozone depletion, etc.

Results and discussion

Reduction of climate change impacts over 2015-2050

Figure 3 illustrates the evolution of climate change impacts between 2015 and 2050 for both assessed pathways. A first observation can be made on the reduction of climate change impacts by 32% and 49% between 2015 and 2050 for the Base and Paris Agreement Pathways, respectively. These decreases appear different from the GHG reductions anticipated in the pathway narratives. For example, in the Paris Agreement Pathway, a reduction of 95% of GHG emissions in 2050 compared to 1990 level is modeled. The European Commission reported a decrease of 22% between 1990 and 2016 (EU Commision 2019), meaning that a decrease of 93% should be apparent between 2015 (assumed the same as in 2016) and 2050 in the Paris Agreement Pathway. A decrease of 49% in climate change impacts (in kg-CO2 equivalent) is however obtained with the LCA model.

An explanation for such differences may stem from the inclusion of the full life cycle in the LCA study, as opposed to the main focus on greenhouse gas emissions occurring within the EU28 geographical boundaries in the TIMES PanEU model. The climate change impacts of fossil fuel-based energy technologies are driven by the combustion processes, while those of renewables sources like wind turbines or photovoltaics are stemming from their production stage. As a consequence, the switch from fossil fuels to renewables tend to shift the climate change impacts outside EU28, if renewable energy technologies are produced outside Europe and imported thereafter. This may therefore limit the actual decrease in anticipated greenhouse gas emissions.

On the other hand, it should be noted that potential reductions of GHG emissions in regions outside Europe are not considered in the LCA model, which may then tend to overestimate the GHG emissions in these regions (because of no time differentiation factoring in the decreases in emission intensities), and lead to underestimate the overall decrease in the global GHG emissions associated with the two pathways. An estimate of the true decrease in GHG emissions should therefore expected to range between the reduction values used in the pathway modelling (in TIMES model) and the reduction values reported above.

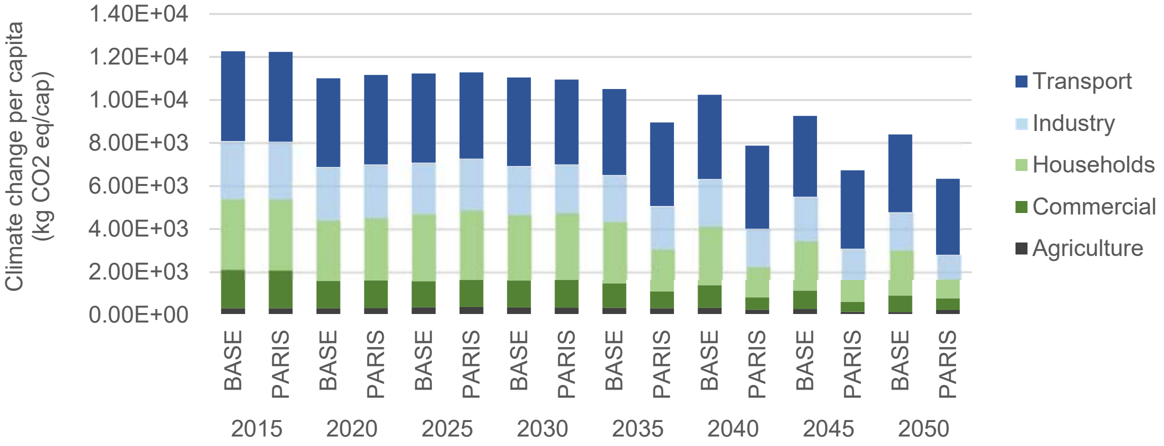

Figure 3. Trends for climate change impacts (per capita) in EU28 between 2015 and 2050 for both Base and Paris Agreement Pathways

It could be additionally noted that the value of 12,000 kg-CO2eq/capita in EU28 for 2015 (for both pathways) seems in a reasonable range, considering that the assessment is comparable to a consumption-based assessment (i.e. taking into account impacts from activities outside EU28 as a result of consumption in EU28). Typical carbon footprint in EU28 is estimated to be approx. 15,000 kg-CO2eq/capita. This also includes non-energy-related contribution from the agriculture sector, the cement sector, and the land use and land use change influence on CO2 emissions. Hence, a minor overestimation may also be present in the results from this study. Based on this quality check for climate change impacts, it is relatively safe to assume that the LCA model is overall consistent (although discrepancies for other types of impact categories may still be present, if substance-specific inconsistencies are present in the LCIs of the model).

Environmental impact trends over time: occurrences of burden-shifting

In Figure 4 the evolution of six selected environmental impact categories from 2015 to 2050 is illustrated. The impacts are indexed on 2015 and the figure, thus, indicates the relative change each year. Below is provided a synthesis of the main results, followed by a brief analysis of each of the 6 impact categories.

It is overall observed that environmental burden-shifting occurs within the pathways, some being common to both pathways while others being unique to either one of the two. For example, climate change is reduced more in the Paris Agreement Pathway than in the Base Pathway, while the opposite is true for human toxicity impacts (cancer effects). Likewise, some impact categories like land use or water use (water scarcity) seem to show an increase in both pathways, suggesting that major modelling choices in the pathway modelling in TIMES model explain those trends (assuming that no inconsistencies lie in the LCA model, which should be checked). Besides those increasing impacts, other impacts tend to remain at similar levels between 2015 and 2050 (e.g. freshwater ecotoxicity). This demonstrates that the definition of the pathways in the TIMES model targeted the decrease of emissions of greenhouse gases (climate change impacts showing largest decrease) and some air pollutants (e.g. particulate matter), while disregarding other causes of environmental impacts. These specific environmental issues should thus be better addressed in further modelling of energy systems in models like the TIMES PanEU model.

Climate change

For the Base Pathway, climate change impacts remain fairly stable until 2030 (7-10% reduction), then decrease until 2050, where a 32.2% reduction in climate change impacts compared to 2015 is reached (see also Section Reduction of climate change impacts over 2015-2050). For the Paris Agreement Pathway the impacts remain in the same range as for the Base Pathway until 2030 (7-11% reduction). However, in 2040 climate change impacts are reduced by 35.6% (thereby exceeding the reductions achieved by the Base Pathway), and in 2050 climate change impacts end up being reduced by 48.2%. See also Section Reduction of climate change impacts over 2015-2050 for specific interpretation of climate change impacts and their reduction over time.

In conclusion, the Paris Agreement Pathway seems to lead to a higher reduction in climate change impacts compared to the Base Pathway (16 percentage-points), but most of the decrease is only operated after 2030.

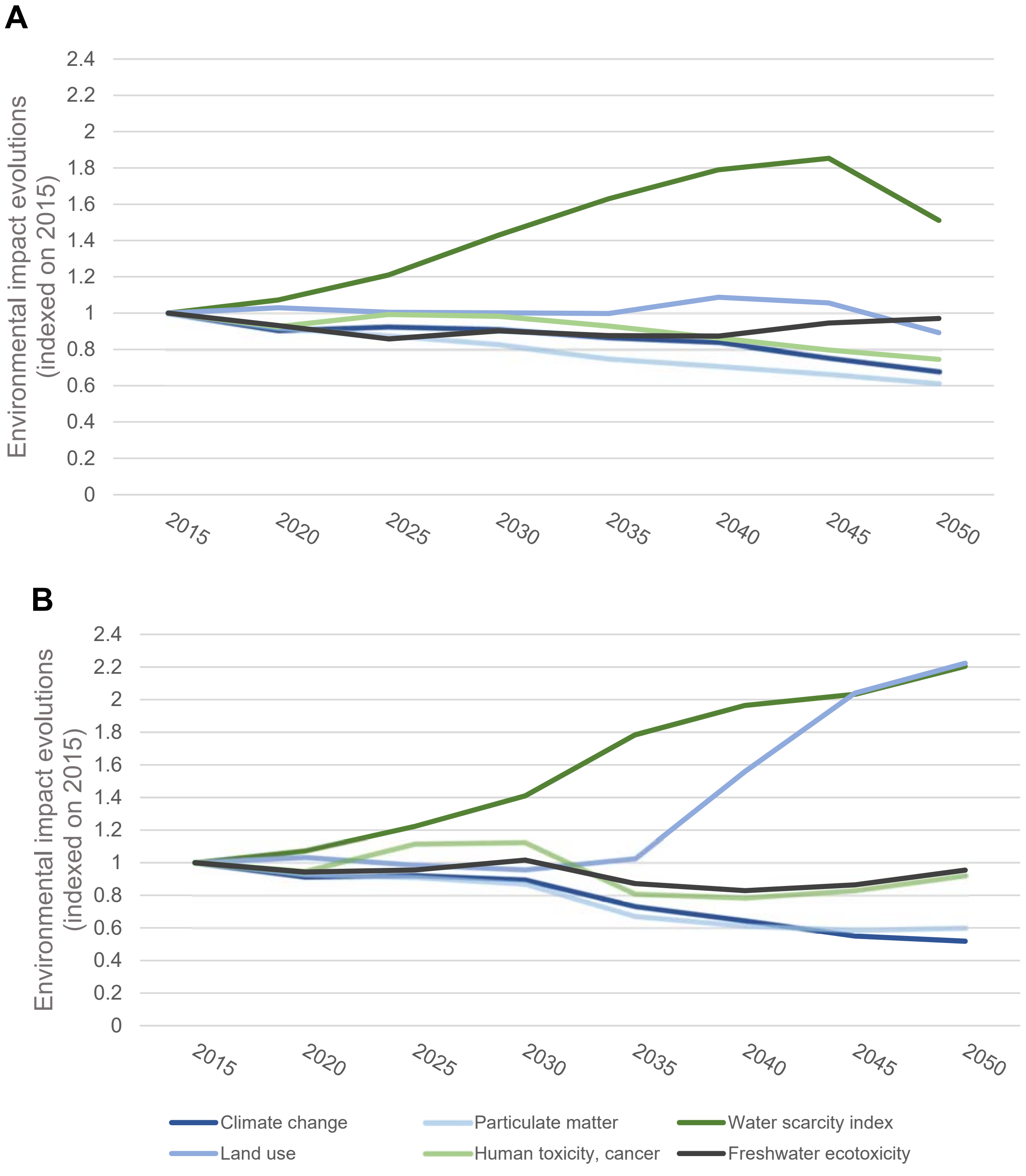

Figure 4. Environmental impacts from 2015 to 2050 for (**A**) Base Pathway, and (**B**) Paris Agreement Pathway (bottom) for the impact categories Global warming, Particulate matter, Water scarcity index, Land use, Human toxicity (cancer), and Freshwater ecotoxicity. The results are indexed on results for 2015, thus showing the relative change over time.

Particulate matter formation

The Base Pathway and the Paris Agreement Pathway both show reductions in impact from 2015 to 2050. The two pathways follow a similar trajectory, although the Paris Agreement Pathway leads to a dramatic drop in particulate matter impacts around 2035 (almost 20 percentage-points) followed by a stagnation at around 39-40% reduction in impacts compared to 2015-level until 2050. Although the reduction is steadier for the Base Pathway, a same reduction of nearly 39% compared to 2015-level is reached by 2050.

In conclusion, both pathways tend to lead to a reduction in particulate matter impacts of around 39% in 2050. The Paris Agreement Pathways ensure a quicker reduction in impacts (a reduction of 33% is already seen in 2035, where the Base Pathway will not reach this level until 2045).

Water scarcity index

Both pathways show a dramatic increase in the water scarcity index. For the Base Pathway the increase is steady until 2045 reaching an 85% increase, but drops to 51% in 2050. For the Paris Agreement Pathway the increase continues to 2050 reaching a level of 120% compared to 2015-level.

In conclusion, in both pathways, the results seem to indicate that water scarcity problems are generated in both pathways, reflecting a potential burden-shifting. These results should however be considered with caution due to possible gaps in water flows in the LCIs of the LCA model; this aspect should be checked for consistency in further work (not possible here due to time limitations).

Land use impacts on biodiversity

For the Base Pathway impacts related to land use remain fairly stable throughout the time period, reaching a maximum reduction of 11% by 2050, after a maximum increase of 9% in 2040. For the Paris Agreement Pathway impacts remain similarly stable until 2035, after which there is a sudden increase of 56% compared to 2015 levels. This increase continues until 2050 where the impacts show increases of 122% compared to 2015.

In conclusion, for the Base Pathway it appears that technological developments and changes to the energy systems have very limited effects on impacts related to land use. For the Paris Agreement Pathway it appears that some changes and modelling choices in TIMES (in technology) causes a change in 2040. A check of the LCIs in the LCA model is also warranted to ensure that this is not caused by inconsistencies in the LCA model. It should however be noted that this unexpected pattern only applies to one pathway, while the LCA model was built generic for any pathway; only inputs from TIMES therefore influence the observed discrepancies between the two pathways results.

Human toxicity, cancer effects

For the Base Pathway impacts related to human toxicity cancer are fairly stable until 2030 where a steady reduction begins and continues until 2050, at which point a 26% reduction compared to 2015 is reached. For the Paris Agreement Pathway the impact level is rather unstable, first showing a small reduction of 5%, followed by an increase of 11-12% the following 10 years (2025 and 2030) compared to 2015 (i.e. an increase from 2020 of 16-17 percentage points). This is followed by a reduction in 2035, 2040, 2045 of 17-22% (i.e. a reduction of 28-34 percentage-points), ending with an overall 8% reduction from 2015-levels (i.e. an increase of 9-14 percentage-points from 2045).The evolutions of technology distribution in the Paris Agreement Pathway as modeled in TIMES model is likely to explain such varying trend.

In conclusion, the Base Pathway reaches the highest reduction of 26% compared to 2015-level. It appears that it does not lead to increases in impacts at any point, contrary to the Paris Agreement Pathway where impact levels are more unstable.

Freshwater ecotoxicity

For both the Base Pathway and the Paris Agreement Pathway the impacts remain fairly constant throughout the time period, and with little overall decrease and a situation in 2050 at the same level as the one in 2015. For the Base Pathway only reductions are observed between the 5-year periods, with a minimum reduction of 3% (2050). For the Paris Agreement Pathway an increase of 2% is observed in 2030, while all other years show reductions of 4.5-17% (2050 and 2040 respectively).

In conclusion, it appears that technological developments and changes to the energy systems have very limited effects on freshwater ecotoxicity impacts, which still remain.

Per-capita environmental impact results

Per-capita environmental impact results can help put results into perspective as well as check the plausibility of the results (in terms of overall range or order of magnitude obtained). In the assessment for climate change impacts, it could be observed that the value of 12,000 kg-CO2eq/capita is found for EU28 in 2015 (for both pathways) –see Figure 5A. This result falls within a reasonable range, considering that the assessment is comparable to a consumption-based assessment (i.e. taking into account impacts from activities outside EU28 as a result of consumption in EU28). Typical carbon footprint in EU28 is estimated to be approx. 15,000 kg-CO2eq/capita (Hertwich and Peters 2009). This also includes non-energy-related contribution from the agriculture sector, the cement sector, and the land use and land use change influence on CO2 emissions. Hence, a minor overestimation may also be present in the results from this study. Based on this quality check for climate change impacts, it is relatively safe to assume that the LCA model is overall consistent (although discrepancies for other types of impact categories may still be present, e.g. substance-specific inconsistencies are present in the LCIs of the model). It can be noted that the contribution of energy systems to climate change impacts fall to 6 and 8 tonnes CO2eq/capita by 2050 for the Paris Agreement and Base Pathways, respectively.

With respect to particulate matter formation and human toxicity, cancer effects, similar analyses may be done although with more difficulty to put the results in perspective (Figure 5B-C). For human health damages from particulate matter formation, approximately 1.7 E-2 DALY/capita is found in 2015, reducing to 1.0 E-2 DALY/capita by 2050 (Figure 5C). At the EU level, assuming stable population, this corresponds to a total health damage from particulate matter caused by consumption of energy systems in EU28 of 8.6 and 5.1 million DALY in 2015 and 2050, respectively (approximately the same for both pathways). Comparatively, with the use of ECOSENSE in REEEM (see Deliverable 5.2, Schmid et. al.), approximately 2.8, 2.0 and 1.9 million DALY were found to stem from the energy systems in EU28 in 2015 for both pathways, in 2050 for the Base Pathway and in 2050 for the Paris Agreement Pathway, respectively. These values are assumed comparable with our study results, despite focusing on main air pollutants (and not just particulate matter and its precursors); damages to human health from ambient air pollution have been found to link primarily to particulate matter (Lim et al. 2012). A relatively important gap therefore distinguishes the two sets of results, which are likely explained by the difference between the scoping of the energy systems included in the assessments. While the current study considers a full life cycle and thus accounts for damages resulting from particulate matter stemming from activities in all life cycle stages of the system (inside and outside EU28), the impact assessment study with ECOSENSE only considers the air pollutants emitted from operation of the energy systems in EU28. It should also be noted that different assumptions lie in the modelling of the human health damages between the ECOSENSE model and the LCIA methods used in the current study.

As illustrated in Figure 6A-F, the transport sector tends to become increasingly predominant in the different environmental impacts between 2015 and 2050 for both pathways. This is a result of the reduction of environmental impacts in the electricity and heating systems (incl. cooling), which transitions to renewables-based energy sources between 2015 and 2050, while transport systems in the Base and Paris Agreement Pathways continue to mainly rely heavily on internal combustion engines, with fuels based on biomass and natural gas. However, it should be noted that several road transport processes were created with major assumptions due to lack of data for modelling their emissions; in those cases, conventional technologies were used, which might lead to overestimate the actual emissions from road transportation, and hence tend to amplify the contribution of the transport sectors in the total environmental burden of energy systems

Yet, the results of this assessment suggest the need for energy policy-makers to focus on this component of the energy systems and ensure transitions to more environmentally-sustainable transport systems. When doing so, a full life cycle perspective and a broad coverage of environmental problems should be included in the assessment to provide reliable support for decision-making. In addition the refining of the modelling to better capture emissions from new technologies for road transportation should be investigated and factored in.

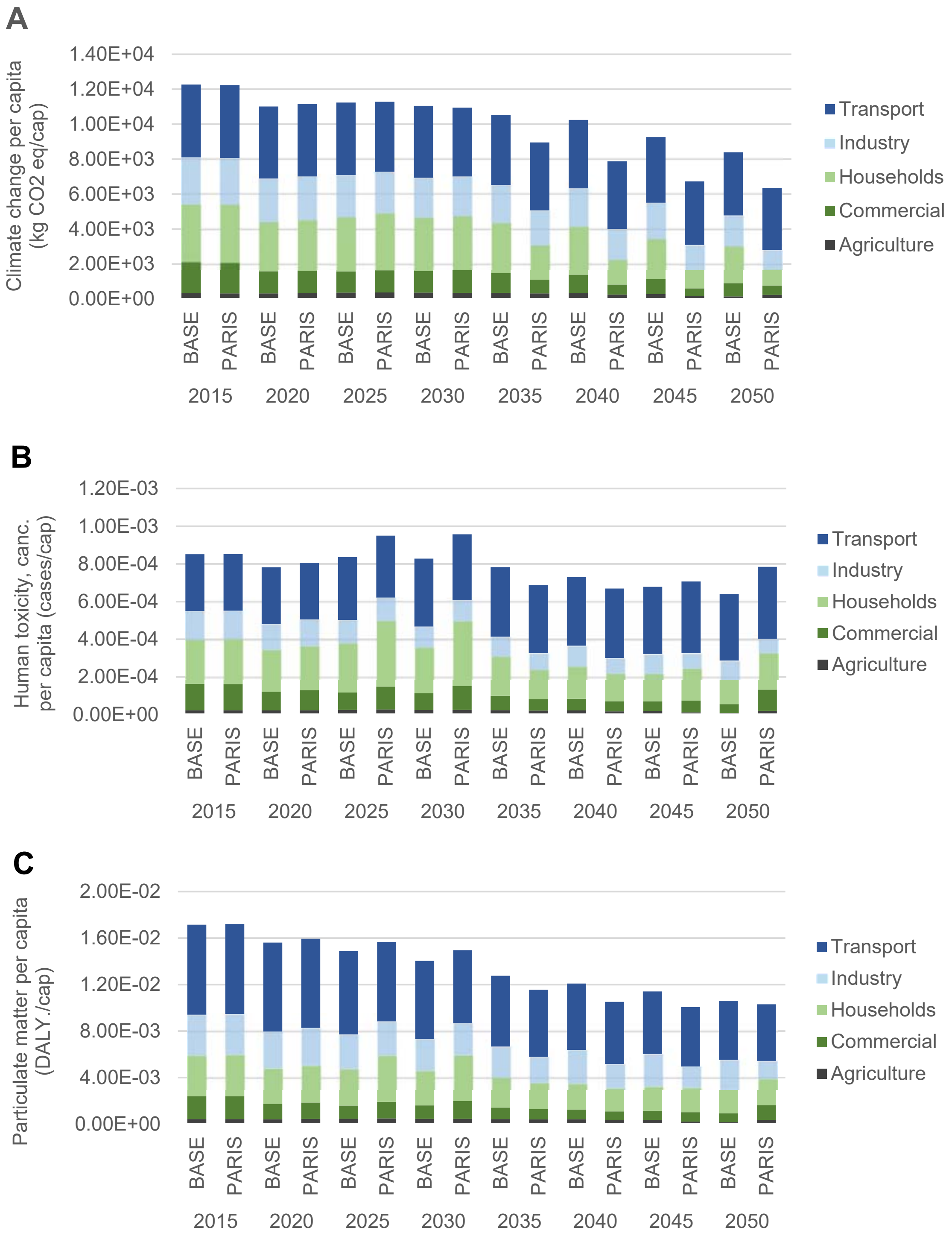

Figure 5. Per-capita impact results for EU28 for both Base and Paris Agreement Pathways for selected impact categories: (**A**) climate change, (**B**) human toxicity, cancer effects, and (**C**) particulate matter formation

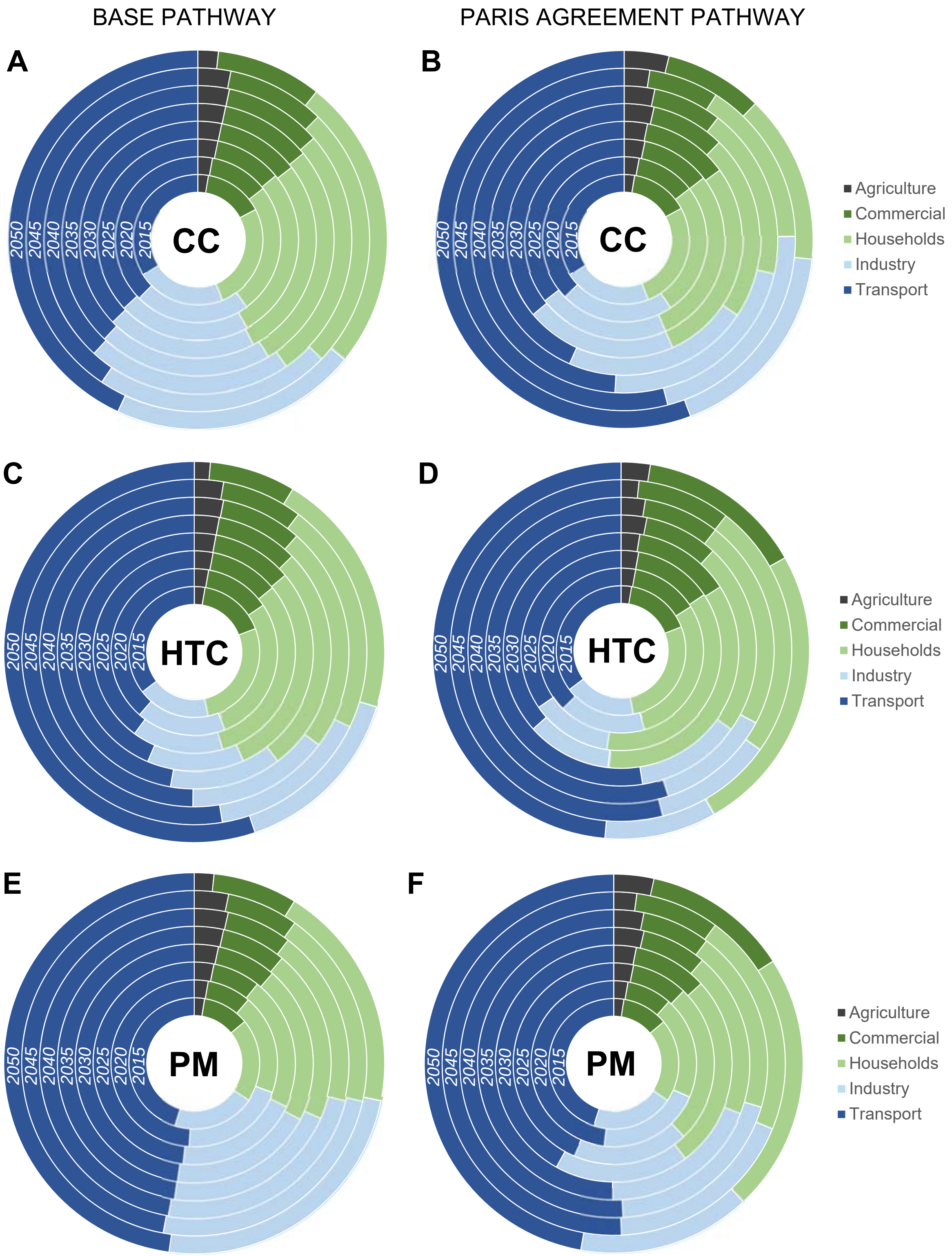

Figure 6. Sector distribution for climate change (CC, Figs. **6A-B**), human toxicity cancer-effects (HTC, Figs. **6C-D**) and particulate matter (PM, Figs. **6E-F**)) for the Base Pathway and Paris Agreement Pathway.

Total human health damages

The total human health damages have been computed from the LCA study for EU28 –see Figure 7. The results can be compared to those obtained with the ECOSENSE model, although the latter only includes air pollutants from operations of the energy systems. It can be observed that the total damages from the LCA study are equivalent to approx. 17 million DALYs in 2015 and decrease to 12 million DALYs in 2050 for both Base and Paris Agreement Pathways (fig. 7A). As noted in the previous sections, overestimations are expected in these estimates, particularly in future years due to the modelling of regions outside Europe using the same technology efficiencies – and hence emission intensities – as today (no time differentiation). Yet, factoring in this overestimation, the obtained results would still remain higher than the results reported when using the ECOSENSE model, where approximately 2.8, 2.0 and 1.9 million DALY were found to stem from the energy systems in EU28 in 2015 for both pathways, in 2050 for the Base Pathway and in 2050 for the Paris Agreement Pathway.

As indicated in Section Per-capita environmental impact results, the different scoping between the two assessments explain part of this difference since the ECOSENSE model focuses on the emissions during the operation stage of the energy system, while the LCA study includes the entire life cycle of the energy systems, from extraction of raw materials through production and installation and operations up to end-of-life. The difference in impact contributors to the total human health damages is another cause for the discrepancies. The assessment from the ECOSENSE model considers emissions of few air pollutants, while the LCA study encompasses all environmental stressors contributing to human health damages. Hence, it includes contribution from climate change, water stress and carcinogenic and non-carcinogenic effects induced by chemical releases like metals and organic substances (see Figure 7B). It should be noted that both the LCA study and the ECOSENSE study are complementary as the former expresses the potential life cycle impacts associated with the function of meeting the energy demand in EU (aggregated over time and space), while the latter has a focus on the actual health impacts taking place, from the changes in air pollutant concentrations modelled at local scales.

Figure 7B illustrates that contribution, showing that particulate matter formation, climate change and toxicity of chemical releases are the three main contributors to human health damages from energy systems in EU28. In terms of emissions, this relates to emissions of particulate matter (and its precursors, like SOx, NOx, NH3), greenhouse gases, and metal and organics substances. As depicted in Figs. 7C-D, for both pathways, transport sector and to a lesser extent households are the main drivers of these heath damages (e.g. 46% and 23%, in 2050 in the Paris Agreement Pathway, respectively), followed by the industry and commercial sectors (14 and 13%). Agriculture has a much lower contribution (3%).

These results demonstrate the need to assess environmental impacts in a systemic and holistic perspective, including all life cycle stages (and not just the operations within EU) as well as a broad spectrum of environmental problems.

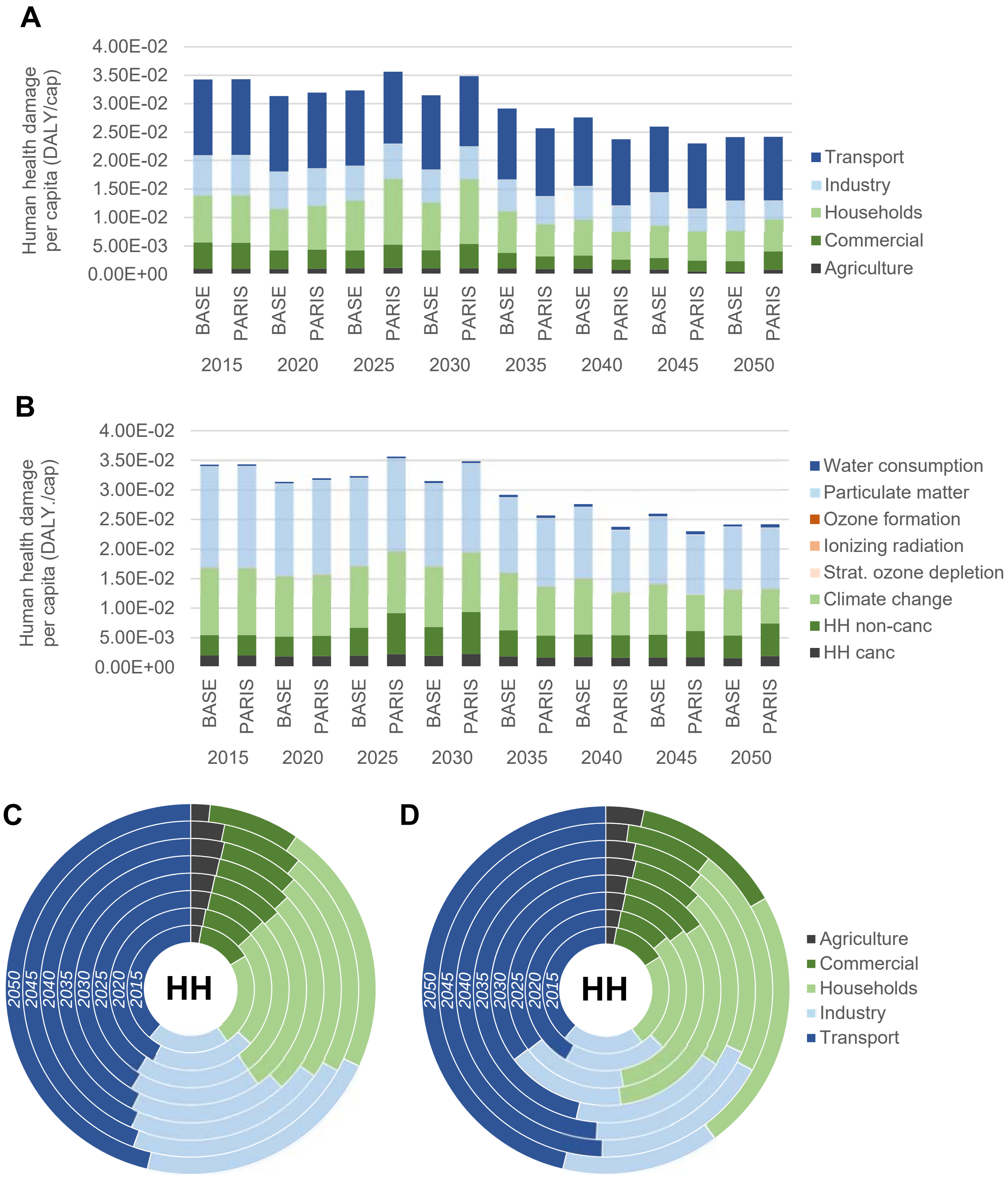

Figure 7. Total human health damage assessment results in EU28 over 2015-2050 for both Base and Paris Agreement Pathways, with (**A**) evolutions of total EU28 damages over time, (**B**) contribution of different environmental impact categories, and (**C-D**) Sector distribution trends, respectively. HH: Human health damages, 'canc': cancer effects.

Conclusions and recommendations

A life cycle assessment study was performed to gauge the life cycle environmental impacts of all energy systems in EU 28 over 2015-2050. A comprehensive model was developed building atop ecoinvent 3.3 database to generate 7275 new processes, covering activities taking place within the entire value chains of all energy systems operated in EU28. This model was built to match the high technological resolution of the TIMES PanEU model and it was parameterized geographically and temporally to cover each of the EU28 countries (+ Norway and Switzerland) and each considered year within the period 2015-2050. This parameterization was mainly affected within a supporting Excel model, which connected, via 33,112 links, to the LCA software SimaPro for performing the environmental impact assessments. Such model development, with its differentiation in space, time and technology, has never been achieved before.

The application of the LCA model on two of the pathways (i.e. Base and Paris Agreement Pathways) showed that the reduction of climate change impacts differs from the reduction of GHG emissions embedded in the pathways narratives. This was mainly explained by (i) differences in scoping, with the narratives mainly focusing on EU28 geographical boundaries (although Paris Agreement Pathway also includes a wider perspective) while the current study includes the full life cycle of the energy systems (hence a global scope), (ii) limitations in the LCA model, which does not include time differentiation in processes occurring outside EU, meaning that emission intensities are modeled the same as in 2015, thus leading to potential overestimations of the GHG emissions outside EU.

Out of the assessment, neither of the Paris Agreement or the Base Pathways seem to perform better than the other. Taking the total human health damages, they end up at the same level of decrease between 2015 and 2050 (decrease of ca. 30%). However, it must be noted that environmental trade-offs occur, with some environmental impact categories tending to decrease more in one pathway over another, e.g. climate change decreasing more in Paris Agreement than in Base Pathways, and vice versa, e.g. cancer effects from released chemicals (aka “human toxicity, cancer effects”, ‘HH canc’). It was also found that some environmental impacts tended to increase between 2015 and 2050, regardless of which pathway was considered (e.g. water scarcity). Overall, the general trends in the environmental impacts were observed to be increasingly driven by the transport sector, which for example contributed to approx. 46% of the human health damages in 2050 in both pathways.

Our findings therefore illustrate the importance of considering a full life cycle perspective when assessing energy systems, and not just considering their operations and/or the related activities within the EU region. Such systemic and broad scoping is the only way to avoid environment burden-shifting from occurring. For example, the climate change impacts of fossil fuel-based energy technologies are driven by the combustion processes, while those of renewables sources like wind turbines or photovoltaics are stemming from their production stage. As a consequence, the switch from fossil fuels to renewables tend to shift the climate change impacts outside EU28, if renewable energy technologies are being imported. Likewise, it is as important to include a large spectrum of environmental problems to provide a complete overview of which environmental problems are predominant in the total environmental burden, where potential environmental trade-offs and burden shifting from one impact to another arise and which ones to prioritize in decision-making processes. A main recommendation is therefore to include such a holistic perspective when assessing energy systems to enable provision of reliable and unbiased support to policymakers.

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PART II: CRITICAL MATERIALS ASSESSMENT

Task Description

The main task description for task 5.3 of the REEEM project, as it relates to critical materials, sets out the core aims and objectives of the project as follows:

"Many of the key technology investments of a future low carbon society rely on and increase the demand for critical materials. This task will identify these critical materials and analyse the likeliness of availability bottlenecks. Starting with a literature review, these materials will then be mapped against the technologies included in the Integrated European Model, taking into account the uncertainties as described in the literature. The pathways developed in WP1 will be used to assess the material requirements of each pathway. These material requirements will then be further evaluated against the causes of criticalities to assess whether bottlenecks seem likely and under what conditions."

Scoping and Setting of Objectives

For the purposes of determining firm outputs and deliverables from Work Package 5.3, the research team has proposed the following activities:

a) A literature review on material criticality as it pertains to the broader REEEM project
b) An assessment of the materials demands implied by the technological transitions depicted in the Integrated European Model (specifically the scenario outputs from the TIMES-PanEU energy systems optimisation model conducted under Work Package 6)
c) A bottleneck assessment to determine whether and which materials could provide challenges to the transitions depicted in the REEEM scenarios

Literature Review

This section addresses objective (a) as set out in the section *Scoping and Setting of Objectives*.

Defining Material Criticality

Resource assessments represent an important component of the global discourse on society and the environment. Transitions to new technologies and new arrangements for delivering energy services to end users can create new demands on upstream supply chains, not only for fuels and primary energy vectors, but also for raw materials. In this context the OECD has recently adopted Coulomb et al.'s [1] definition of "critical materials", conceived of as non-renewable minerals for which *"the risk of disruptions in supply is relatively high and for which supply disruptions will be associated with large economic impacts"*. In a general sense, it can therefore be said that some materials are "critical" to the energy transition if they are an important component in the manufacture and delivery of clean energy technologies.

Typically, overall indices of material criticality are determined through multi-criteria analysis using different indicators, with the selection of those indicators varying widely between studies [2]. The various metrics used to assess the criticality of resources are very diverse and might include; the importance of selected raw materials to various national economies, the extent to which supplies are concentrated in relatively few regions, whether or not the resources can be substituted, the political stability of producer nations, and the ability of the considered materials to be recycled [3]. As an example of two contrasting approaches for developing criticality indices we can compare the work of:

- Graedel [4], whose taxonomy involves supply risk (including regulatory and geopolitical risks), environmental implications of resources, and their vulnerability to supply restriction; against that of
- Mason et al. 2011 [5], whose framework for determining criticality explores resource availability (geographical concentration, geological characteristics), resource addiction (dependence), and the availability of alternatives (substitutability and recoverability).

The concept of "criticality" of raw materials is of course a relative one. There are varying perspectives on which materials can be said to be "critical" depending on who the decision makers are, the geographical or regional conditions for the assessment, and the time horizon used, amongst other factors. The identity of the decision makers in particular, can radically shift the perspective on whether materials are "critical" or not. This is because the objectives, the types of risks encountered, and the ability to mitigate or adapt to them vary significantly between national governments and firms [4]. For example, a specific organisation is mainly focused on the criticality of a specific material on its product line, whereas governments consider the broader national industries and populations [4].

The methodological differences between studies and the importance of perspective (i.e. global, national, individual firms) in determining whether resources are "critical" or not, have caused some researchers to call into question the validity of "criticality" as a broad concept [6,7]. For example, a wide-ranging review of material supply risk assessment methods found that indicator selection and weighting can risk becoming an essentially arbitrary exercise, with the situation being further exacerbated when good quality data on specific resources is unreliable or unavailable [8]. Recent studies (e.g. Helbig et al. [9]) certainly stress that "criticality" can only be usefully discussed when the context and framing of the criticality assessment is made clear.

This is not to say that some materials do not consistently appear in futures-oriented criticality studies – for example, there are often common findings between material assessments with disparate perspectives and methodologies. For example, a critical meta review of studies by Erdmann and Graedel [2] identified manganese, gallium, niobium, indium, rhodium, palladium, and platinum as being critical in all cases, while half of the studies (e.g. see [10–12]) also had tungsten, niobium, and indium in common.

Critical Materials and Energy Technologies

Table 4 gives an overview of materials mapped against different energy technologies from a structured review of the literature encompassing both European and global-scale studies. The reviewed studies varied widely in terms of their:

- **Scope and system boundary:** some studies take an economy-wide perspective, while others focused on individual economic sub-sectors
- **Level of technological aggregation**: some studies explored material criticality at the level of individual components, like batteries; while others defined criticality in relation to finished consumer products, such as automobiles

- **Definitions of criticality:** criticality was defined via different metrics in different studies and the terms used to describe varying grades of criticality also varied e.g. “critical” vs. “near-critical”, “high” vs. “moderate” risk etc.

These factors made direct A to B comparisons between the studies difficult (i.e. it is difficult to establish conclusively that materials of a certain kind are always “critical”) but the table still serves as a useful overview of which materials might be important in relation to various energy technologies and various economic sectors.

Table 4. Critical materials identified in various studies mapped against energy technologies

Sectoral Focus	Technologies	Critical Materials	References	Geographical Scope of Referenced Studies
Residential and Commercial Buildings	Lighting	Terbium (Tb) Yttrium (Y) Europium (Eu)	Moss et al. 2013 [13], US Department of Energy 2010, 2011 [14,15], US National Research Council 2008 [16]	European Union, United States of America
		Gallium (Ga) Germanium (Ge) Indium (In)	Moss et al. 2013 [13]	European Union
		Lanthanum (La)	Grandell et al. 2016 [17], US National Research Council 2008 [16]	Global, United States of America
		Dysprosium (Dy)	US Department of Energy 2010, 2011 [14,15]	United States of America
		Cerium (Ce) Gadolinium (Gd)	US National Research Council 2008 [16]	United States of America
Transport	Vehicles	Dysprosium (Dy) Neodymium (Nd)	Marscheider-Weidemann et al. 2016 [18,19], Moss et al. 2013 [13], US Department of Energy 2010, 2011 [14,15], US National Research Council 2008 [16], Hatayama and Tahara 2015 [20], AEA Technology 2010 [21]	Global, European Union, United States of America, Japan, United Kingdom
		Praseodymium (Pr)	Marscheider-Weidemann et al. 2016 [18,19], Moss et al. 2013 [13], US Department of Energy 2010, 2011 [14,15], US National Research Council 2008 [16], AEA Technology 2010 [21]	Global, European Union, United States of America, United Kingdom
		Palladium (Pd) Platinum (Pt)	Buchert et al. 2009 [11], US National Research Council 2008 [16]	Global, United States of America
		Yttrium (Y) Aluminium (Al)	Marscheider-Weidemann et al. 2016 [18,19]	Global
		Zirconium (Zn)	Zhou et al. 2019 [22]	China
		Graphite (C)	Moss et al. 2013 [13]	European Union

		Samarium (Sa) Gadolinium (Gd) Rhodium (Rh)	US National Research Council 2008 [16]	United States of America
	Electric vehicles	Cobalt (Co)	Marscheider-Weidemann et al. 2016 [18,19], US Department of Energy 2010, 2011 [14,15], Zhou et al. 2019 [22], AEA Technology 2010 [21]	Global, United States of America, China, United Kingdom
		Lithium (Li)	Marscheider-Weidemann et al. 2016 [18,19], Buchert et al. 2009 [11], US Department of Energy 2010, 2011 [14,15], US National Research Council 2008 [16], AEA Technology 2010 [21]	Global, United States of America, United Kingdom
		Manganese (Mn)	Marscheider-Weidemann et al. 2016 [18,19], Zhou et al. 2019 [22]	Global, China
		Terbium (Tb) Copper (Cu)	Marscheider-Weidemann et al. 2016 [18,19]	Global
		Indium (In)	Grandell et al. 2016 [17]	Global
		Lanthanum (La) Cerium (Ce)	US Department of Energy 2010, 2011 [14,15]	United States of America
		Chromium (Cr) Nickel (Ni)	Zhou et al. 2019 [22]	China
		Lead (Pb)	AEA Technology 2010 [21]	United Kingdom
Energy Supply	Wind turbines	Neodymium (Nd) Dysprosium (Dy)	Marscheider-Weidemann et al. 2016 [18,19], Moss et al. 2011 [23], US Department of Energy 2010, 2011 [14,15], AEA Technology 2010 [21]	Global, European Union, United States of America, United Kingdom
		Praseodymium (Pr)	Marscheider-Weidemann et al. 2016 [18,19], Moss et al. 2013 [13], US Department of Energy 2010, 2011 [14,15]	Global, European Union, United States of America
		Terbium (Tb) Copper (Cu)	Marscheider-Weidemann et al. 2016 [18,19]	Global
		Chromium (Cr) Nickel (Ni) Manganese (Mn)	Zhou et al. 2019 [22]	China
	Photovoltaics	Tellurium (Te) Gallium (Ga)	Buchert et al. 2009 [11], Grandell et al. 2016 [17], Moss et al. 2011 [23], US Department of Energy 2010, 2011 [14,15]	Global, European Union, United States of America
		Indium (In)	Grandell et al. 2016 [17], Moss et al. 2011 [23], US Department of Energy 2010, 2011 [14,15]	Global, European Union, United States of America

		Silver (Ag)	Grandell et al. 2016 [17], Zhou et al. 2019 [22]	Global, China
		Ruthenium (Ru)	Grandell et al. 2016 [17]	Global
		Tin (Sn) Cadmium (Cd) Selenium (Se)	Zhou et al. 2019 [22]	China
	Concentrating Solar Power (CSP)	Silver (Ag)	Grandell et al. 2016 [17]	Global
	Advanced alloys for supercritical fossil fuel power plants	Rhenium (Re)	Moss et al. 2011 [23]	European Union
	Nuclear reactors	Hafnium (Hf) Indium (Hf)	Moss et al. 2011 [23]	European Union
	Solid Oxide Fuel Cells (SOFCs)	Yttrium (Y) Zirconium (Zr) Scandium (Sc) Nickel (Ni) Lanthanum (La) Strontium (Sr) Manganese (Mn)	Marscheider-Weidemann et al. 2016 [18,19]	Global
		Lanthanum (La)	Grandell et al. 2016 [17]	Global
	Proton exchange membrane fuel cells (PEMFCs) and direct-methanol fuel cells (DMFCs)	Platinum (Pt)	Moss et al. 2013 [13], US National Research Council 2008 [16]	European Union, United States of America
	Thermoelectric generators	Tellurium (Te) Antimony (Sb) Germanium (Ge) Silver (Ag) Bismuth (Bi) Lead (Pb) Silicon (Si) Hafnium (Hf) Zirconium (Zr) Manganese (Mn) Cobalt (Co) Nickel (Ni) Iron (Fe) Tin (Sn) Ruthenium (Ru)	Marscheider-Weidemann et al. 2016 [18,19]	Global

European Perspectives on Criticality

Within European Union, criticality has historically been defined as a function of two main factors, those being *supply risk* and *economic importance*, with a formal European Community (EC) definition developed in 2011 [24]. Under the 2-axis EC definition, *supply risk* was conceived of as a function of (i) resource concentration, (ii) the standard of governance in the territories where the resources are concentrated, (iii) the ease of resource recycling; and (iv) the ease of resource substitution; while *economic importance* was determined simply as a function of overall demand per sector and the contribution of that sector to gross value added (GVA). The EU definition of resource criticality has evolved over time and researchers have suggested a number of improvements [25], but at the time of writing (Q2 2019) no formal European definition exists for assessing the criticality of materials in the energy sector specifically.

That is not to say that there has not already been significant work in this area. Europe has been and remains a leading global region in terms of climate policymaking and conducting research into prospective clean energy transitions. The EU has stringent policy objectives of reducing greenhouse gas (GHG) emissions by 40% (as compared to 1990 levels) by the year 2030 [26] and achieving net-zero emissions (termed as “climate neutrality”) by the year 2050 [27] in line with the Paris Agreement [28] brokered by the United Nations Framework Convention on Climate Change (UNFCCC). As part of this push on decarbonisation policy, the EU has conducted research into the raw material implications of the Strategic Energy Technology Plan (SET-Plan) [29], which highlights six key technologies: nuclear power, solar photovoltaics and concentrated solar power, wind and bioenergy, carbon capture and storage and electricity grids. Future resource demands and potential bottlenecks for these six technologies were comprehensively assessed in work by scientists at the EU’s Joint Research Centre (JRC) [23,30] who then also expanded their line of enquiry to cover 11 additional technologies in a follow up study [13]. This work concluded that six rare earth elements (dysprosium, europium, terbium, yttrium, praseodymium and neodymium) and two metals (gallium and tellurium) could be considered "critical", while four further metals were classified as "near critical” (graphite, rhenium, indium, and platinum). However, several years have passed since this work was carried out and the policy environment has seen a number of changes. Existing work in this area does not yet take a long-term perspective out to 2050 or take into account the possibility of multiple technological transition pathways towards European energy and climate objectives, something which we hope to address here in this report.

Material Criticality Definition for REEEM

For the purposes of carrying out the assessment of raw material criticality contained in this report, we have focused here on understanding whether or not there is an arising supply risk to EU SET plan technologies, given the focus of the REEEM project on the transformation of the European energy sector. In terms of our scope we therefore build heavily on prior work undertaken for the European Union’s Joint Research Centre (JRC) by Moss et al. [13,23,30] and apply this to the REEEM pathways developed under WP1.

Based on the literature review, we have elected to consider demand for the following 14 raw materials shown in Table 5. We are agnostic in terms of our definition of criticality and have instead opted to include materials that have frequently appeared in criticality studies associated with energy technologies, and in particular are important to EU SET plan priority technologies and electric drivetrain vehicles.

Table 5. Materials considered in this report

Material	Chemical Symbol
Cobalt	Co
Dysprosium	Dy
Europium	Eu
Gallium	Ga
Indium	In
Hafnium	Hf
Lanthanum	La
Lithium	Li
Neodymium	Nd
Platinum	Pt
Praseodymium	Pr
Tellurium	Te
Terbium	Tb
Yttrium	Y

The technologies considered are highlighted in Table 6, with further details on the assumptions behind each technology category provided in Appendix D.

Table 6. Clean energy technologies considered in this report

Energy Technology	Notes
Lighting	We consider both: - *energy efficient fluorescent lamps* - *lamps based on light emitting diode (LED) technology*
Electric Vehicles	We consider a range of body styles – *small/medium/large passenger cars, light duty vehicles, heavy duty vehicles, buses*; and also capture multiple automotive drivetrain types, including: - *hybrid electric vehicles* i.e. where the battery is used only for storing energy from regenerative braking and is not charged directly from mains power - *battery electric vehicles* i.e. where a rechargeable battery provides the main motive power source - *plug-in hybrid electric vehicles* i.e. where electrical energy from a rechargeable battery is combined with at least one other stored fuel source for motive power (fuels include gasoline, diesel, ammonia, methane, biofuels and hydrogen from various production paths)
Wind Turbines	We assume a mix of permanent magnet and electromagnet *wind generators*, as well as a blend between geared and gearless transmissions for both *onshore* and *offshore* installations
Photovoltaics	We assume a mixture of *crystalline* and *thin-film* photovoltaic technologies
Nuclear Reactors	We assume that new nuclear power deployments take the form of conventional *pressurised water reactors (PWRs)*
Fuel Cells	We consider both: *Solid oxide fuel cells* for stationary applications *Proton exchange membrane (PEM) fuel cells* found in vehicles
Electricity Storage Batteries	We consider: *Electrical storage batteries* for stationary applications *Electrical storage batteries* found in vehicles

We have, in this section, reviewed the existing literature and developed a method agnostic list of materials that could prove to be critical for the development of the European energy system. It needs to be noted here that, in light of the complexities involved in defining what “criticality” actually means, our analysis needs to be considered within the confines of the definitions, material and technology portfolios we use here. Other definitions could well introduce additional materials and technologies to the list, reflecting the issues around broad definitions of criticality discussed earlier in this document.

Materials Demand Assessment

This section addresses objective (b) as set out in the section *Scoping and Setting of Objectives*.

Methods

The REEEM Project has three core transition pathway narratives [36], all of which will be considered in our analysis:

- **Coalitions for a Low Carbon Path:** this pathway achieves an 80% reduction in energy-related emissions by 2050 as compared to 1990 levels, with energy suppliers responsible for shouldering the majority of the burden of delivering decarbonisation through large-scale investments in renewable energy generation. There is only limited progress in terms of technological innovation in the end-use demand sectors and individual consumers retain a largely passive role in the transition.
- **Local Solutions:** this pathway also achieves an 80% reduction target for 2050 across the EU. However, in this case, a significant fraction of the climate mitigation effort is driven by communities and individuals in the end-use demand sectors, and the pathway features the accelerated renovation of residential buildings and the rapid uptake of low carbon technologies in both households and road transport.
- **Paris Agreement:** in this pathway the EU takes a globally leading role in fulfilling the aims and objectives of the Paris Agreement and undertakes an ambitious decarbonisation effort, with a target of achieving a 95% reduction in emissions by the year 2050. This results in a deep shift towards low carbon technologies in nearly all sectors of the economy.

The process for determining the demand for critical materials can be summarised as follows:

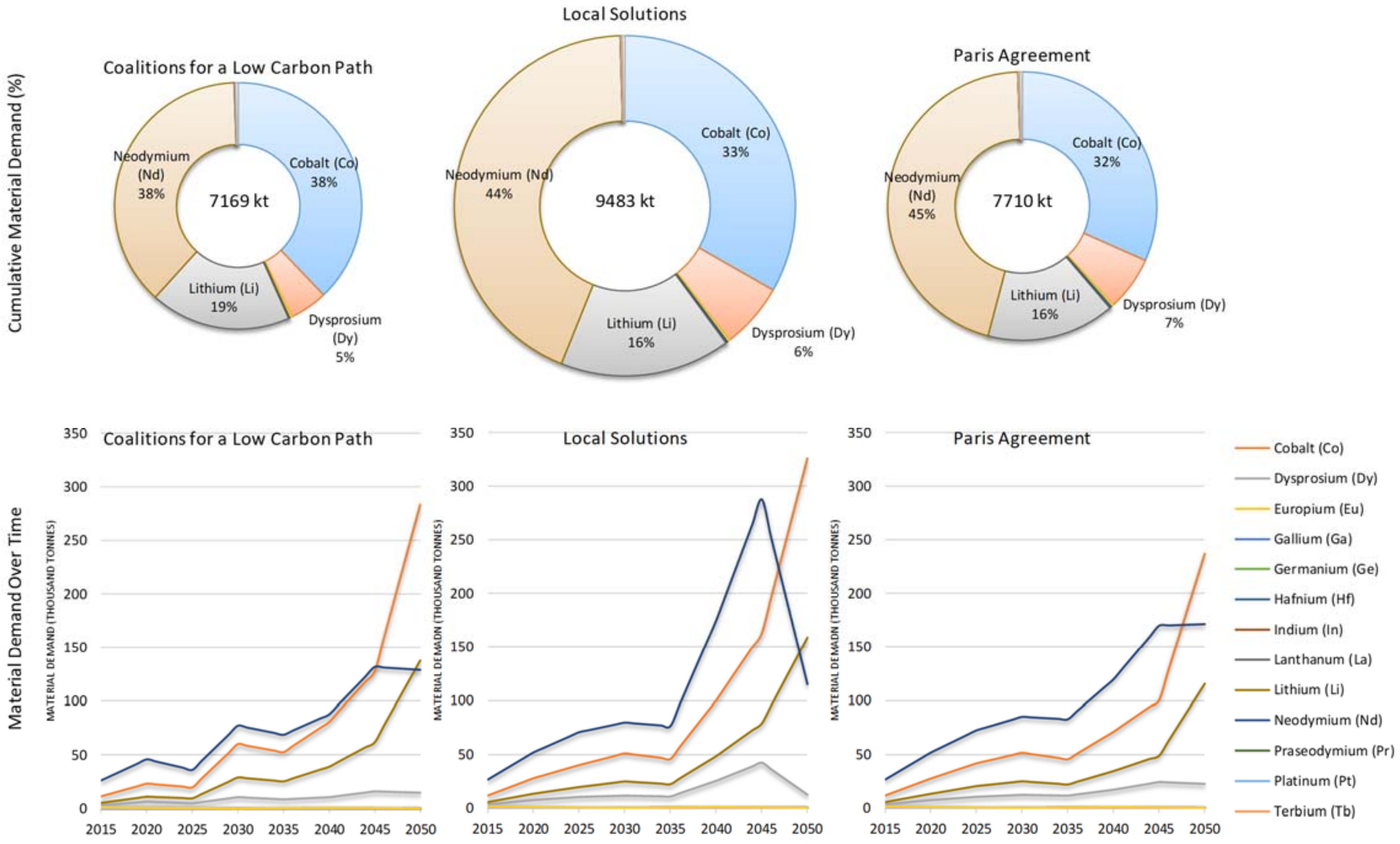
1. Model outputs from the TIMES Pan-EU model (which sits at the centre of the REEEM modelling framework) were used to determine the flow of investments (in capacity units) in each of the three pathways (*Coalitions for a Low Carbon Path*, *Local Solutions*, and *Paris Agreement*). This involved mapping the technologies explicitly captured in TIMES Pan-EU to the seven key technology categories identified in Table 3, including where necessary differences within each category (such as between different types of lighting or different vehicle types as these are captured in the model).
2. Material demand on a per unit basis for each of the 14 materials identified in Table 2 was estimated for each of the seven technology categories identified in Table 3. Detailed assumptions on the representative technologies used and the sources drawn from for establishing per unit material demands are included in Appendix A.
3. By combining technology investments across the time horizon from (1) with estimated per-unit material demands from (2), the cumulative material demands implied under each scenario was established. Note that we do not explicitly assess demand for non-EU regions or non-energy demands, as these go clearly beyond what the REEEM modelling framework is

able to capture. We do, however, use the current global data to qualitatively interpret the implications of the projected European energy related material demands.

Results

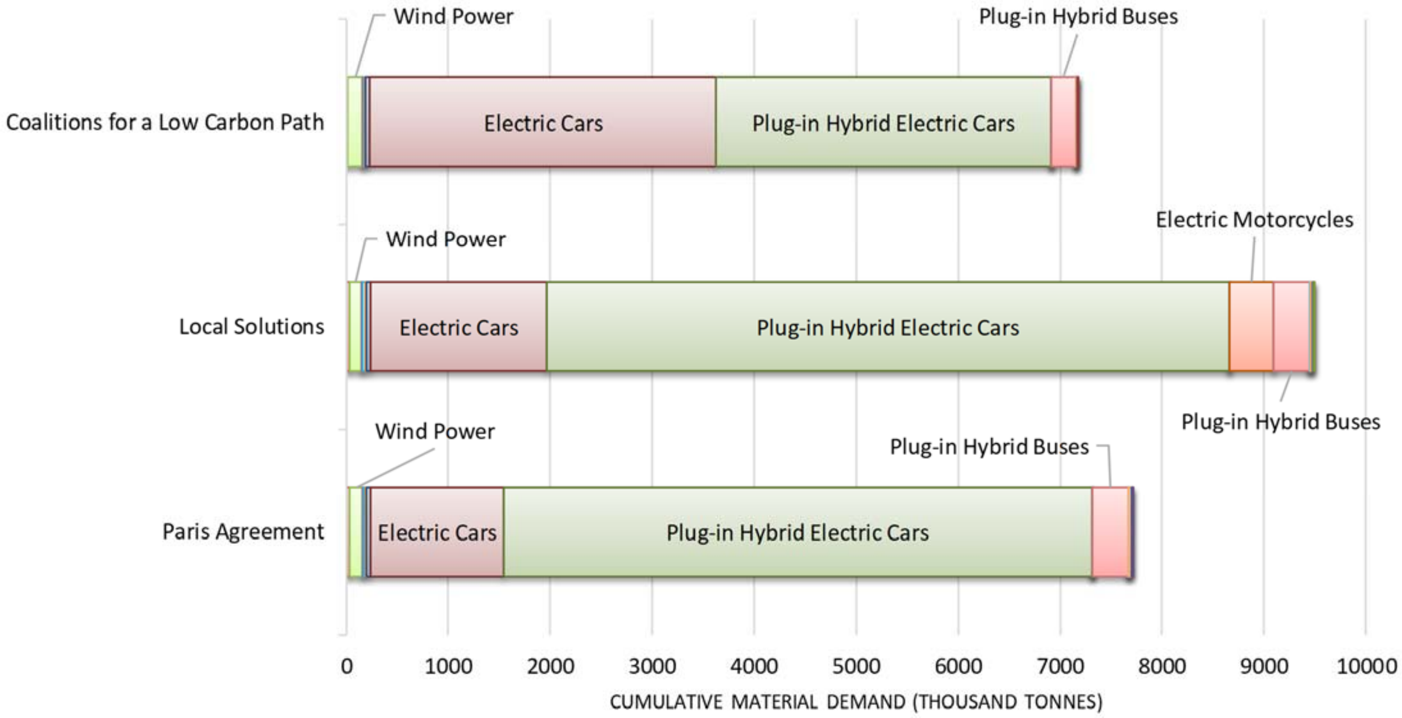
Figure 8 illustrates results for each of the REEEM pathways, both the shares of cumulative material demand across the modelled time horizon and the detailed view of how material demand changes over time for individual elements. Both the *Coalitions for a Low Carbon Path* and the *Paris Agreement* pathways represent similar levels of total material demand at 7169 kt and 7710 kt respectively, although the split between the materials differs slightly. The *Local Solutions* pathway has the highest material demand of all at 9483 kt, likely owing to the significantly larger role that a transition to low carbon end-use demand technologies has in this case.

Figure 8. Material Demand for Each REEEM Pathway



Despite the differences in overall cumulative demands, it can be seen that the same four metals dominate the transition in all three pathways. These are cobalt (32-38%), dysprosium (5-7%), lithium (16-19%) and neodymium (38-45%), all of which are elements that are particularly important for energy dense batteries and high-performance magnets. Figure 9 illustrates a breakdown of material demand for each pathway by energy technology. From this chart the major drivers behind the demand for materials can be seen clearly. In all three pathways, electric vehicles and plug-in hybrid electric vehicles are the major sources of material demand. This doesn't automatically mean that the materials and technologies with the highest demands would necessarily be those that are the most likely to be the source of supply bottlenecks. Supply risks on a per material basis are affected by a range of factors, such the volume of estimated reserves and the required speed of production ramp up to meet demand. We consider supply risks in detail in the next section.

Figure 9. Cumulative Material Demand by Technology



Bottleneck Assessment

This section addresses objective (c) as set out in the section *Scoping and Setting of Objectives*. In our bottleneck assessment for individual materials, we focus mainly on the issue of *supply risk,* as defined in the literature (e.g. [4]) as opposed to other dimensions of criticality such as the environmental implications of material production. Graedel et al. [4] define separate supply risk assessment methods for the medium-term (defined as 5-10 years), and the long-term (defined as 10+ years). For the medium-term, Graedel's method is to explore:

- **Geological, technological and economic risks:** measured as a function of depletion time (based on estimated reserves) and the companion metal fraction for each material (i.e. where a desired material is only found in nature in the ore of another material)
- **Social and regulatory risks:** measured as a function of potential policy resistance to mining activity and the overall human development index (HDI) of the countries where mines are located
- **Geopolitical risks:** measured as a function of the quality of governance in producer countries and whether or not these are heavily concentrated or not in a few countries

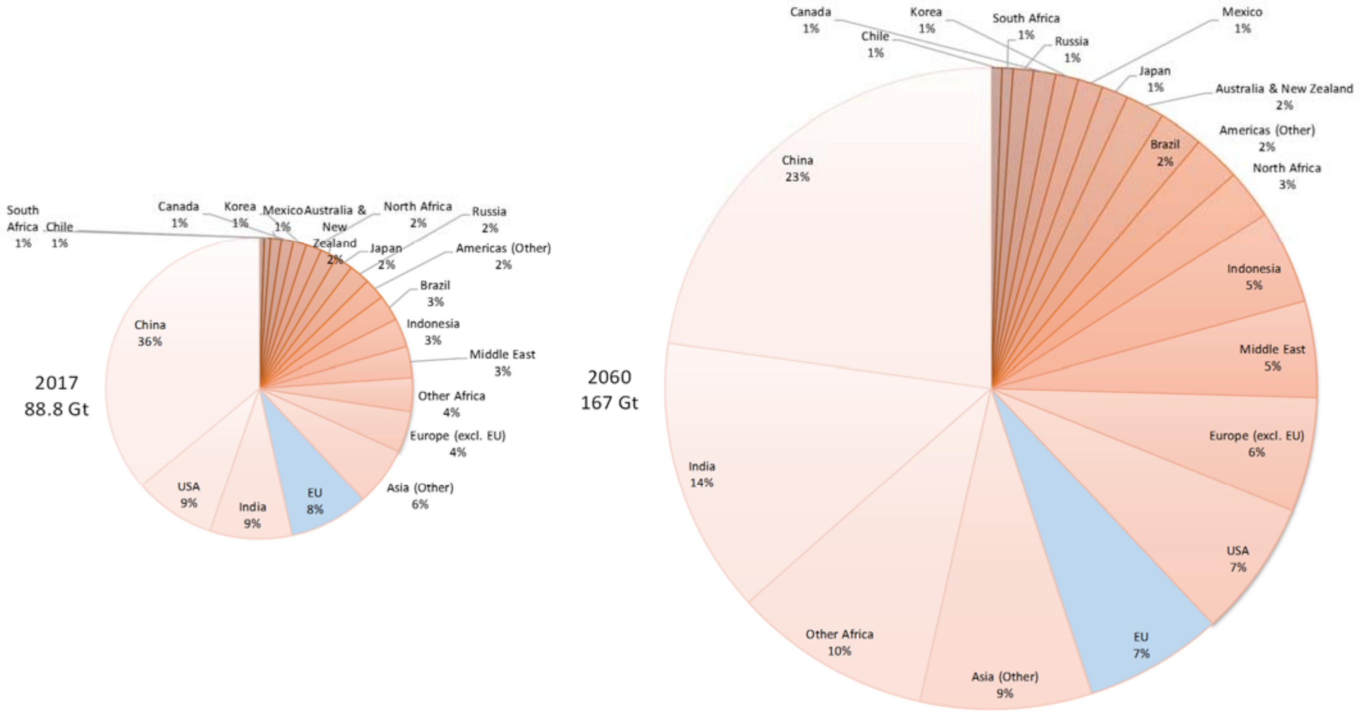
In the long-term, only geological, technological and economic risks feed in to Graedel's overall definition of supply risk, with the assumption being that social, regulatory and geopolitical risks can be mitigated over time at the global scale. In this report, we will explore both medium-term and long-term supply risks as they pertain to the REEEM pathways. Our process for assessing supply risks is as follows:

a) **Geological risk:** we assess the total cumulative EU energy systems related demand implied by the REEEM pathways against estimates of global reserves. If the pathways exceed known global reserves, or capture a significant share of them (considering the focus on EU and the energy sector alone) then this implies that there could be a geological risk if new resources cannot be discovered.
b) **Economic risk:** we assess annual demand implied by the REEEM pathways against global production levels. If the material demands in the pathways represent a very large fraction of current global production, there could be economic risks as the EU competes with other regions and also as the energy technology sector competes with other economic sectors. Also, rapid increases in production capacity may be difficult to achieve for technical reasons, or be possible but only at a large cost.
c) **Geopolitical risk:** we assess whether or not large concentrations of production and/or reserves are located in relatively few regions or if they are diversified.

European Union Materials Demand in a Global Context

Before proceeding to the formal bottleneck assessment, it merits highlighting that in absolute terms, the materials demands associated with the future transition in EU energy sector technologies (in the order of a few hundred kt) are of course small relative to the global picture. The OECD estimates [31] that global demand for raw materials in 2017 was around 88.8 Gt, with the EU representing approximately 8% of the total at 7.45 Gt. This is projected to increase to 167 Gt by 2060, with the EU roughly maintaining its global share (7%, 11.5 Gt). These projections capture future material demand across all sectors, technologies and materials (including common ones such as steel and concrete), and take into account future changes to population size, demography (particularly age) and economic growth.

Figure 10. Relative Demand for Global Materials in 2017 and Projections for 2060 (based on OECD [31])



Overview of Supply Risks in REEEM Pathways

Table 7 compares estimates of total global reserves (including % concentration in known deposits by country) against the cumulative material demands implied by the three REEEM pathways. In the case of gallium and indium, authoritative quantitative estimates of total global reserves do not exist, which reflects a degree of uncertainty surrounding the availability of these materials.

Table 7. Estimated Global Production and Reserves for Assessed Materials

Material	**Range of Cumulative Demand Implied by REEEM Pathways (kt)**	**Estimated Global Reserves 2018 (kt)** [32]	**Concentration of Estimated Reserves**
Cobalt (Co)	2,440 – 3,152	6,900	Democratic Republic of Congo (49%) Australia (17%)
Gallium (Ga)	22 – 23	-	-
Indium (In)	6 – 15	-	-
Hafnium (Hf)	0.01 – 0.13	73 (all Zirconium Ores)	Australia (58%) South Africa (19%)
Lithium (Li)	1,187 – 1,534	14,000	Chile (57%) Australia (19%)
Platinum (Pt)	2 – 6	69 (all PGMs)	South Africa (91%)
Rare Earths	3,094 – 4,741	120,500	China (37%) Vietnam (18%), Brazil (18%)
Tellurium (Te)	6 – 16	31	China (21%) United States (11%)

Table 8 summarises the estimated global primary production of selected materials as reported by the U.S. Geological Survey [32] and the main producer countries with an indicator of how concentrated resources are (% of production from the primary producer).

Table 8. Estimated Global Production for Assessed Materials

Material	**Estimated Global Primary Production 2018 (tonnes)** [32]	**Main Producer Countries in 2018 and their Production Shares (%)**
Cobalt (Co)	140,000	Democratic Republic of Congo (64%)
Gallium (Ga)	410	China (95%)
Indium (In)	750	China (40%) Republic of Korea (31%)
Hafnium (Hf)	1,500 (Zirconium Ores)	Australia (33%) South Africa (23%)
Lithium (Li)	85,000	Australia (60%) Chile (19%)
Platinum (Pt)	160	South Africa (69%)
Rare Earths	24,000	China (70%) Australia (12%), United States (9%)
Tellurium (Te)	440	China (68%)

Supply Risks by Material

Materials are assessed here on a case by case basis. As detailed disaggregated statistics on the global and regional supply of individual rare earths are generally not available, they are considered here in aggregate as a single category.

Cobalt (Co)

Cobalt is used in fuel cells, electricity storage batteries, and electric vehicle technologies (including hybrids).

Geological risk: Cumulative demand for cobalt across the three REEEM pathways varies as a fraction of estimated global reserves by 35-46%. This is a very high fraction of global demand for a single sector in a single world region, and so should be considered a geological risk.

Economic risk: All three REEEM pathways see a rapid increase in the EU's demand for cobalt, rising at an average rate of 10% per annum across the time horizon. In the pathways this has the effect of cobalt demand increasing 3-4x from 2015 levels by the mid-2030s, rising steadily to around 50 kt/pa. After this point the demand accelerates still further, reaching annual demands of around 300 kt by 2050 in the *Coalitions for a Low Carbon Path* and *Local Solutions* pathways, and around 250 kt in the *Paris Agreement* pathway. Global primary production in 2018 is of the order of 140 kt/pa. Global supply would need to significantly increase in the period to 2050 if the REEEM pathways are to be realised. The risk of supply demand imbalances and price volatility for cobalt may be non-negligible. Not only are other global regions besides the EU likely to require cobalt for their own use, and may have demand growing at similar rates to the EU, but cobalt is also used in non-energy technologies and sectors, such as the manufacturing of high performance metal alloys. We have not assessed the potential for cobalt recycling to mitigate economic risks in this report, but we would note that global recycling rates for cobalt are high at around 32%, and have the potential to increase still further.

Geopolitical risk: The largest production of cobalt at the time of writing (64%) is in the Democratic Republic of Congo (DRC), which also has the largest single fraction of known reserves (49%). The DRC has historically suffered through prolonged periods of political instability, including a six-year civil war that lasted from the late 1990's to the early 2000s. Ongoing conflicts in the region have the potential to disrupt production and cause market prices to fluctuate.

Gallium (Ga)

Gallium demand is associated with the deployment of LED lighting and solar photovoltaic (PV) panels.

Geological risk: The geological risk for gallium could not be assessed due to a lack of conclusive data on estimated reserves.

Economic risk: Modelled EU demand for gallium under the REEEM pathways sees two periods of peak demand – one in the 2020's and another in the 2040's, with both peaks being around 1,000 tonnes in all three pathways. In the medium term peak (2020) for all three pathways, the gallium demand for EU lighting is around three times the entire global primary production in 2018, which suggests that a large demand supply imbalance could cause sharp price increases and represent a supply bottleneck. This is particularly true when one considers that future demand in non-EU regions for LED lighting might be growing at a similar rate to the EU across the assessed time horizon, putting further pressure on gallium production.

Geopolitical risk: At the time of writing, the single largest producer of gallium is China, which has a 95% production share. This effectively makes the EU dependent on a single producer in the medium term, which represents a potential supply bottleneck.

Indium (In)

Indium demand in the REEEM pathways is associated with solar photovoltaics, LED lighting, and nuclear power plants.

Geological risk: The geological risk for indium could not be assessed due to a lack of conclusive data on estimated reserves.

Economic risk: Indium demand in the REEEM *Local Solutions* pathway represents the most challenging case out of all three REEEM pathways. This sees indium demand spiking in the period 2035-2050 to levels that are around 3.6x current global production levels. While this does give a multi-decadal timeframe for ramping of indium production rates to meet demand, indium is not only used in the energy sector but is also found in multiple non-energy sector applications (for example display manufacturing). This, combined with the fact that future EU demand is likely to be a fraction (7-8%) of the global whole, with other world regions likely to be also growing their own demands for indium-dependent energy technologies, means that indium should be considered a potential supply bottleneck from an economic risk perspective.

Geopolitical risk: Global indium production is mainly concentrated in China (40%) and South Korea (31%). Both countries are collocated in the same region of the world and would use the same navigation channels for transportation of raw materials to Europe, so we have conservatively flagged indium as being at risk from a geopolitical perspective.

Hafnium (Hf)

Hafnium demand is associated with nuclear reactors.

Geological risk: Cumulative demand for hafnium (associated with the deployment of nuclear power technologies) across the REEEM pathway scenarios is low, and less than 2% of estimated global reserves (if we take zirconium ore deposits as a proxy for hafnium). We assess the geological risk as being negligible.

Economic risk: Maximum demand for hafnium in any year from the modelling suggests that it will not exceed 11 tons/pa. This is a very small percentage (less than 1%) of global primary production, and so we assess the economic risk here as being negligible.

Geopolitical risk: Hafnium is available from a comparatively diverse range of sources, with the largest concentrations found in Australia (33%) and South Africa (23%). Individual hafnium producers in countries with major nuclear power programmes (like Areva in France) are able to supply millions of tonnes per annum, so it seems likely that the EU could be able to meet its own requirements in this case.

Lithium (Li)

Lithium is a key material found in high energy density batteries, both those used for grid-scale electricity storage and those found in electric or hybrid vehicle technologies.

Geological risk: The REEEM pathways, as modelled, use large quantities of lithium. Total cumulative demands for lithium across the transition time horizon amount to 8-11% of global reserves. We assess the geological risk as low.

Economic risk: Lithium demand, like that for cobalt, is associated in the REEEM pathways with battery technologies, particularly for electric drivetrain vehicles. As with cobalt, demand for lithium grows at a rate of around 10% per annum across the time horizon. This is broken into two distinct segments; while there are per-pathway differences demand generally grows steadily until the 2030s before encountering a step change in demand and rapidly accelerating in the period 2030-2050. EU demand alone for lithium in the REEEM pathway projections for 2050 is between 115-160 kt/pa, which is more than double that of the entire global production level in 2018 (85kt). A multi-decadal transition does of course leave enough time for global production levels to increase to meet new demand. But lithium is likely to be in great demand not only from non-EU regions transitioning to electro-mobility but also in battery applications beyond the specific technologies and sectors that we have focused on here in this report. The economic risk is non-negligible due to the risk of price volatility from demand supply imbalances.

Geopolitical risk: The world's two major sources of lithium are Australia, which is responsible for 60% of production in 2018, and 19% of known global reserves; and Chile, which only accounts for 19% of production but has 57% of estimated reserves. Both countries are in the Southern Hemisphere but are physically distant from one another, which makes the prospect of a regional catastrophe affecting both nations at the same time a remote possibility. We assess the geopolitical risk as low.

Platinum (Pt)

Platinum demand in the REEEM pathways is associated with fuel cells.

Geological risk: Cumulative demand for platinum in the three REEEM pathways is between 2-6 kt, which represents 3-9% of estimated reserves, taking all platinum group metals (PGMs) as a proxy for geological availability. We assess the geological risk as being low.

Economic risk: The REEEM *Coalitions for a Low Carbon Path* pathway represents the most challenging case for platinum demand, with a peak in demand in 2035 and another in 2050. The 2035 peak demand for EU platinum is around 2.5x the estimated entire global production of the metal in 2018. Without a detailed assessment of the headroom in existing platinum mining operations or the roadmap for new mine development it is challenging to comment conclusively on the feasibility of ramping up production to meet this demand. However, when taking into account environmental permitting, planning regulations and economic redistribution policies, opening a new mine can often take as much as 5-10 years. Platinum also has many competing applications in the industry and manufacturing sectors besides fuel cells, and of course the EU will be in competition with other world regions for the material who may also be growing their demand at similar rates to the EU. We therefore have assessed platinum as being at risk of supply bottlenecks in the economic dimension. One potential mitigating factor that we have not assessed in detail is platinum recycling. Platinum is widely recycled at a rate of around 70% globally [31], with some future scope for further improvements.

Geopolitical risk: Global production of platinum group metals (PGMs) is heavily concentrated in South Africa, which supplies 69% of world demand in 2018 and is believed to contain 91% of all reserves. Any crisis affecting mine production in South Africa would represent a potential supply shock for EU platinum supply.

Rare Earths[1]

Dysprosium and neodymium feature heavily in the manufacture of electric vehicle motors as well as in wind power generators. Europium and terbium are found in certain energy efficient fluorescent lighting applications. Lanthanum is important both for fuel cells and again, fluorescent lighting. Yttrium features in the manufacture of nuclear reactors, fuel cells, fluorescent lighting, and LED lighting.

Geological risk: All of the REEEM pathways show strong shifts towards technologies that presently rely heavily on rare earths, with dysprosium and neodymium in particular emerging as two of the largest groups of materials in the resource assessment exercise. Although cumulative EU demand for rare earths across the time horizon in all three REEEM pathways is the single largest source of material use, this only represents 3-4% of global reserves. We assess the geological risk therefore as being low.

Economic risk: Demand for rare earths grows strongly in all three REEEM pathways, reaching between 150-200 kt/pa in 2050. Global primary production was 24 kt/pa in 2018, so the technological transitions depicted in REEEM show the EU alone using 6-8x what the entire world produces today. In the medium term, the very rapid increases in demand implied by the modelled technological transitions has the potential to outstrip existing production capacity, especially if other world regions besides the EU see their demand for rare earth-dependent energy technologies growing at similar rates. While production would no doubt rise over time to meet such a strong increase in demand, the risk of price fluctuations and supply interruptions during the interim period remains non-negligible.

Geopolitical risk: China is responsible for 70% of global rare earth production today, with Australia (12%) and the United States (9%) in distant second and third places respectively. There is therefore a strong dependence on a single main source of supply, which introduces geopolitical risks in the near and medium term. In the longer term, deposits of rare earths are much more evenly distributed than the present production pattern, with most reserves found in China (37%), Vietnam (18%) and Brazil (18%).

Tellurium (Te)

Demand for tellurium in the REEEM pathways is driven by the uptake of solar photovoltaic (PV) technologies.

Geological risk: The REEEM pathways imply a cumulative material demand of between 19-53% of total known tellurium reserves, just for supplying demand for EU energy technologies in a world that not only also might need tellurium for energy technology development but which also uses tellurium for a variety of manufacturing requirements (semiconductors, chemicals, glass and ceramics). The large fraction of implied demand in relation to reserves represents a geological risk.

Economic risk: Both the *Local Solutions* and *Paris Agreement* pathways see peaks in tellurium demand of around 900-1000 tonnes/pa in 2035. Meeting this demand from the EU energy technologies sector alone would represents a 2-2.3x increase in global production capacity. As it is likely that the EU will not be the only region that sees increasing uptake of solar PV in the intervening years, the risk of price volatility cannot be discounted.

Geopolitical risk: The largest single producer of tellurium in the present day is China (68%), and in the short and medium term the EU could be exposed to geopolitical risks from any disruptive events that affect this single dominant supplier. In the longer term, however, tellurium reserves are much more

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[1] In this category we discuss dysprosium (Dy), europium (Eu), lanthanum (La), neodymium (Nd), praseodymium (Pr), terbium (Tb), yttrium (Y).

widely distributed. China has the single largest share of reserves but this amounts to only 21% of the global resource.

Overview of Supply Risks

Table 9 below summarises the supply risks for each of the selected materials. Cobalt and tellurium appear to be at risk across all three assessed dimensions. Platinum and the rare earths are not at risk from a geological perspective but are exposed to economic risks due to rapid demand growth and geopolitical risks as a result of high supply concentrations in single countries. Gallium and indium are also clearly exposed to economic and geopolitical risks but the overall geological risk level could not be determined due to a lack of quantitative data on reserves. Lithium is at risk from the economic dimension but is not likely to be affected by geological constraints or geopolitical crises. Finally, hafnium does not appear to be at risk in any of the assessed dimensions.

Table 9. Overview of Supply Risks for Selected Materials

Material	**Risk**		
	Geological	**Economic**	**Geopolitical**
Cobalt (Co)	Yes	Yes	Yes
Gallium (Ga)	-	Yes	Yes
Indium (In)	-	Yes	Yes
Hafnium (Hf)	No	No	No
Lithium (Li)	No	Yes	No
Platinum (Pt)	No	Yes	Yes
Rare Earths	No	Yes	Yes
Tellurium (Te)	Yes	Yes	Yes

Summary of Findings

All three REEEM pathways see their material demands dominated by electric and hybrid road transport vehicle technologies. A number of potential supply bottlenecks exist across the geological, economic and geopolitical dimensions. The most at risk materials are cobalt and tellurium, with a second grouping being platinum, rare earths (particularly dysprosium and neodymium), gallium, and indium. In absolute terms, the *Local Solutions* pathway appears to have the highest cumulative materials demand and is therefore at the greatest risk of being affected by supply bottlenecks, while material demands for the *Coalitions for a Low Carbon Path* and *Paris Agreement* pathways are much lower.

Key mitigation options for the EU are material efficiency, recycling and substitution[2], which should be considered as policy imperatives under all three pathways. A large fraction of the critical material demand assessed in this report arises from the transition to electro-mobility, so per unit estimates of material demand (see Appendix A) for vehicles are a key driver of the report findings. It is worth reflecting that research into material efficiency and component substation has found that rare earth content in vehicle magnets could be reduced through efficient design by up to 40% [33] and that options for electric motors are under development that are free of rare earths entirely [34,35].

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[2] It is often possible to substitute materials from a similar group (albeit with often reduced or altered performance characteristics). An example from the platinum group metals (PGM) would be replacing platinum with palladium, while from rare earths an example would be substituting samarium for dysprosium.

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Appendix A – Countries included in the assessment and their codes

The 28 countries of the European Union are included in the assessment. Wherever applicable, single countries are referred to by their ISO 2-digit codes, as listed in Table A1.

Table A1. ISO codes for EU28 countries

Austria	AT	Estonia	EE	Italy	IT	Portugal	PT
Belgium	BE	Finland	FI	Latvia	LV	Romania	RO
Bulgaria	BG	France	FR	Lithuania	LT	Slovakia	SK
Croatia	HR	Germany	DE	Luxembourg	LU	Slovenia	SI
Cyprus	CY	Greece	GR	Malta	MT	Spain	ES
Czech Republic	CZ	Hungary	HU	Netherlands	NL	Sweden	SE
Denmark	DK	Ireland	IE	Poland	PL	United Kingdom	UK

Appendix B – Documentation of the LCA model

Electricity from conventional power plants (PP)

Construction of the template process for our project (steam turbine)

The coefficient C_2 for the process Water for cooling and the emissions to air and water were calculated using multiple variables in ecoinvent, and it can thus not be extracted directly from the website. To overcome this, the flow value was multiplied by the efficiency to obtain a coefficient equivalent to the ones for the other flows. Ammonia is not present in the ecoinvent inventory. However, as this substance can have important impact on human health a fixed value of 3mg/kWh is assumed based on Koornneef et al. (2010) for all countries.

Construction of the template process for our project (IGCC)

The same structure of power plant as for the Steam turbine has been used, with some changes due to the difference in efficiency of the PP.

Carbon capture and storage (CCS) technologies

The introduction of a CCS process in a PP implies five main changes:

- **CO2 emissions reduction (= carbon capture rate)**
- **Other substances emissions variation (reduction or increase)**
- **Efficiency of the PP reduction (from 5 to 10% depending on the CCS technology)**
- **CCS technology equipment construction and chemicals**
- **CO2 transport & storage**

All these points will be considered individually in this section.

Efficiency of the PP

The installation of a CCS technology causes a reduction in the efficiency of the power plant. This is mainly due to the energy and electricity needed to make the CCS work. Therefore, it is assumed that these efficiencies account for every extra energy requirement, such as extra energy needed for oxygen production in oxyfuel and CO2 compression.

Table B1. Efficiency reductions (NEEDS, 2008)

Technology PP	Technology CCS	PP efficiency reduction [%]		
		(NEEDS 2008)	(Koornneef et al. 2012)	(IEAGHG 2011)
Steam turbine	Post-combustion	7-10 (2025) 5-7 (2030)	8-13	
	Oxyfuel combustion	8-10 (2025) 7-8 (2030)	9-12	
	Retrofit	Same as post-comb		
IGCC	Pre-combustion	6	5-9	

This will impact the process flows as they depend on the efficiency of the PP. It should be noted that the other changes were applied to the initial value, i.e. before the efficiency reduction is applied.

Carbon capture rate

The goal of the CCS is to reduce the CO2 emissions in the air. Thus, the main characteristic defining a CCS technology is the CO2 capture rate.

Table B2. CCS capture efficiency

Fuel	Technology PP	Technology CCS	CCS capture efficiency [%]		
			(NEEDS 2008)	(Koornneef et al. 2012)	Used in the study
Coal	Steam turbine	Post-combustion	90	85-90	90
		Oxyfuel combustion	99.5 (2025) 100 (2030)	90-100	100
		Retrofit	Same as post-combustion		90
	IGCC	Pre-combustion	90	85-90	90
Gas	Steam turbine	Pre comb		85-100	100[a]
		Oxyfuel		90-100	
	Comb cycle	Oxyfuel	100	90-100	100
		Post comb	90	50-100	

[a] used to model combined cycle, Pre-combustion.

The higher capture rate, i.e. the best case scenario, was consistently chosen to reflect future developments in technology.

Other substances, water and waste variation

Because of the difference in the flue gas and the addition of chemicals, some emissions can vary when a CCS technology is added.

Table B3: Other substances variations (Koornneef et al. 2010, 2012)

Fuel	**Tech. PP**	**Tech. CCS**	**Relative variation [%]**					
			Water	Ash	SO2	NOx	PM	NH3
Coal	Steam turbine	Post comb	{32; 96}	{23; 41}	-85 {-100; -40}	-6 {-14; 0}	-29 {-77; 0}	{1650; 4425}
	Steam turbine	Oxyfuel	{33; 35}	/	-94 {-100; -76}	-58 {-100; 0}	-94 {-100; -87}	/
	Steam turbine	Retrofit	Same as Post-comb					
	IGCC	Pre comb	50	/	-55 {-93; -15}	-15 {-24; -4}	0 {-1; 1}	/
Gas	Comb cycle	Oxyfuel	/	/	/	-100	/	/
	Comb cycle	Post comb	81					

Table B4: Other substances variations used in the study

Fuel	**Tech. PP**	**Tech. CCS**	**Relative variation [%]**					
			Water	Ash	SO2	NOx	PM	NH3
Coal	Steam turbine	Post comb	32	23	-100	-14	-77	1650
	Steam turbine	Oxyfuel	33	23[b]	-100	-100	-100	1650[b]
	Steam turbine	Retrofit	Same as Post-comb					
	IGCC	Pre comb	50	23[b]	-93	-24	0	1650[b]
Gas	Comb cycle	Pre comb	50[a]	/	-93[a]	-24[a]	0[a]	1650[b]
		Oxyfuel[c]	33	/	-100	-100	-100	1650[b]

[a] same value as coal, IGCC, pre-comb, for affinity of capture technology.

[b] same as coal, steam turbine, post comb., to be conservative.

[c] same as coal, steam turbine, oxyfuel, for affinity of capture technology.

Again, the higher capture rate was chosen to reflect future developments in technology.

For oxyfuel and IGCC CCS there is no certain data available on ash and ammonia emission changes. According to Koornneef et al. 2010, the (potential) ammonia formed in oxyfuel is injected with CO2, and thereby not emitted, but to be conservative the same figures as in Post-comb is assumed. The same assumption is made for the rest of the cases.

Extra plant construction for CCS technology

In the report from (IEAGHG 2011), it is stated that:

- **A price of 2000$/kW is used for the construction of a new power plant without CCS.**
- **A ratio for capture plant [$/(kgCO$_2$/hr)] to base plant [$/kW] range 0.2 to 0.4 for a coal PP.**
- **The capture equipment cost is considered the same for new and retrofitted power plants.**
- **A retrofitted PP might need an upgrade to be able to welcome a CCS equipment, and this can be converted to an allowance of 500$/kW w/o capture, or 25% of the power plant price without CCS.**

Fowler et al. (2012) estimate a cost of equipment for CO_2 removal and compression of around 30% of the base power plant price.

If we assume the CCS equipment does not require fundamentally different materials compared to the base PP (the infrastructure of the power plants (construction and dismantling) with CO2 capture has been modelled the same way as for the power plants without CO2 capture) and that the material flows is proportional to its costs, the input flow of the Hard coal, PP process can simply be increased to account for the extra cost.

Additionally, the worst-case scenario is considered for the retrofit of PP, so the entire PP needs to have an allowance. So finally:

$F_{\text{total power plant materials}} = F_{\text{base plant materials}} + X_{\text{CCS equipment}} + X_{\text{Allowance}}$
$F_{\text{total power plant materials}} = F_{\text{base plant materials}} + 0.3 * X_{\text{base plant materials}} + 0.25 * X_{\text{base plant materials}}$

$F_{\text{total power plant materials}} = 1.3 * X_{\text{base plant materials}}$ for new PP equipped with CCS equipment
$F_{\text{total power plant materials}} = 1.55 * X_{\text{base plant materials}}$ for retrofitted PP

F is the flow of materials for the power plant with or without CCS and X is the flow of additional materials needed for the CCS. It was assumed that the installation of a CCS technology does not change the lifetime of the PP.

The chemicals used for the CCS process depends on the technology used. (Koornneef et al. 2008) and (NEEDS 2008) have been using a amine-based solvent in the CO2 separation phase of the post-combustion CCS. See Koornneef for the detailed use of the solvent. (IEA 2016) states that amino-based solvents are the most used and (Rao and Rubin 2002) indicates MEA (monoethanolamine based solvent) as the solvent typically used. For now, only MEA input and its emissions (to air) are considered, although HSS (heat stable salts) form as by-products and part of the MEA is reclaimed. NaOH and activated carbon inputs are also considered.

Table B5. Parameters concerning solvent and chemicals use used in this study.

Parameter	Unit	Value	Source
MEA solvent	Kg/t CO2	2.34	Koornneef et al. 2008
MEA emissions to air	Kg/t CO2	8.50E-02	Geomean from (IEA GHG 2006) (0.014-0.047) and (Thitakamol et al. 2007) (0.11-0.72)
NaOH	Kg/t CO2	0.13	(Rao et al. 2004)
Activated carbon	Kg/t CO2	0.075	(Chapel et al. 1999)

Each parameter was adjusted for the tons of CO2 emitted from a normal plant (steam turbine) without CCS equipment.

According to (Carpenter and Long 2017), IGCC with CCS is most likely to be a pre-combustion technology using physical solvents like Selexol. The solvent is a mixture of dimethyl ethers of polyethylene glycol and is used in quantities of 0.03 g/kWh (Odeh and Cockerill 2008).

CO2 transport and storage

Transportation distances within Europe through onshore pipelines was found to be between 200 and 400 km (NEEDS 2008). Transport through a pipeline for CO2 is not available in Ecoinvent, but the available process for natural gas was taken as proxy and modified according to (Wildbolz 2007). The worst-case transport distance was chosen (400 km) and this required recompression of the gas during transport. Energy for recompression was provided in NEEDS, 2008 and Wildbolz, 2007 (average).

(NEEDS 2008) states that the most likely storage site for CO2 to be used in Europe within the next 40 years is geological storage, with two possibilities:

- **Saline aquifer at the depth of 800m**
- **Depleted gas reservoir at the depth of 2500m**

The second type was chosen (conservative choice, as the reservoir is at larger depth) and modelled according to (Wildbolz 2007), assuming that brand new wells would be built, i.e. no reuse of existing wells for depleted gas operations. According to the study, 2 drilling wells (2500 m length each) and an additional monitoring well (1250 m length) are needed (assuming injection rate of 125 kg CO2/s per well and a constant mass flow of approximately 250 kg/s). Besides the construction of the wells, electricity is required for the injection of CO2. The total quantity of CO2 that can be stored in the gas field was assumed to be 410 Mt.

Lignite

As for hard coal, a specific process for electricity production from lignite was not available in ecoinvent for Denmark, therefore data for calculation of the coefficient C2 are a geometric mean taken from the other available countries. This means that C2 and plant efficiencies specific for lignite were used. Besides this, the model resembles the one for hard coal, including the variation of parameters introduced with CCS technology.

Original process used from ecoinvent 3.3	Process available for Denmark
Electricity, high voltage {*X*}| electricity production, lignite | Conseq, U	No

Oil

Steam turbine

A representative process for Denmark is available in ecoinvent and was used. Flows were calculated in the same way as for hard coal.

Original process used from ecoinvent 3.3	Process available for Denmark
Electricity, high voltage {DK}| electricity production, oil | Conseq, U	Yes

Gas turbine

The process is a copy of steam turbine oil plant, but the input of oil power plant infrastructure was replaced with gas turbine, assuming that the same number of pieces was required. Gas turbines are similar to steam turbines except that flue gas is used to turn the turbine instead of steam and, after this, the flue gas is emitted to the air (JRC 2016). Therefore, it was assumed that emissions remain the same as in steam turbine plant. A gas turbine does not have boiler or steam supply; therefore its water requirements should be lower than a steam turbine. However, water requirements were not changed in the model, as no specific documentation was found to support this suspicion.

Combined cycle

Combined cycle gas turbine (CCGT) is the combination of a gas and a steam turbine where the exhaust of gas turbine is used to power the steam turbine. Again, the process is a copy of a steam turbine. The plant infrastructure was replaced with 'Gas power plant, combined cycle', which was the closest process to a combined plant, despite being a gas- instead of an oil-fired power plant. This could underestimate the plant requirements, as the equipment for gasifying the oil was not included in the dataset for natural gas, but infrastructure inputs were considered of minor importance, in the impact assessment, compared to the emissions from the plant operation. Emissions were assumed to be the same as for the steam turbine.

Internal combustion

No representative process is available in ecoinvent, thus internal combustion was modelled as a copy of the steam turbine process.

Natural gas

Steam turbine

A representative process is available in ecoinvent and was used. Flows were calculated in the same way as for hard coal.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {*X*}| electricity production, natural gas, conventional power plant | Conseq, U	No

Gas turbine

A process for natural gas turbine is available in ecoinvent (only for DE and NL) and was used, the inventory is however not very detailed. Every input or emission was calculated in ecoinvent by multiplying C1 with a scaling factor (and not the factor 3.6/efficiency) and no efficiency of the process was indicated. It was assumed that this scaling factor is the normal factor and it was used to extrapolate the efficiency and calculate C2.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {*X*}| electricity production, natural gas, 10MW | Conseq, U	No

Combined cycle

A representative process is available in ecoinvent and was used. Flows were calculated in the same way as for hard coal.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {*X*}| electricity production, natural gas, combined cycle power plant | Conseq, U	No

Combined cycle with CCS Pre-comb and Combined cycle with CCS Oxyfuel

Plant modifications due to CCS technology were considered. When available, values were taken specifically for gas (see Tables 4, 5, 6); otherwise, values from hard coal were assumed.

Internal combustion

No representative process is available in ecoinvent, thus internal combustion was modelled as a copy of the steam turbine process.

Fuel cell

There are three types of processes in ecoinvent for electricity production from fuel cell, but they are only representative for Switzerland. According to (Das et al. 2017), solid oxide fuel cells are mostly used for electricity production, so this type of plant is assumed as a proxy. In the process both electricity and heat (cogeneration process) is produced, but only the allocation-based process is available. As a first approximation, the process delivering only electricity can be used to model a non-cogeneration process for fuel cell. For every input, emission and waste stream, consequential-based unit processes were used. The dataset was also modified to simulate DK, i.e. replacing CH with DK unit processes for input of fuel and emissions of water. Note that the process requires low pressure natural gas input, but for Denmark only high pressure natural gas is available and therefore this process was used. This means excluding energy and emissions for the conversion from high to low pressure. Even though in ecoinvent inputs and emissions do not depend on efficiency, they were modelled using the same formulas used for hard coal, so that each input/emission depends on efficiency of the plant. To calculate C2, the efficiency given in ecoinvent (in SimaPro) for the cogeneration fuel cell plant is used (0.47%). LHV is taken from the process natural gas steam turbine.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, low voltage {CH}| natural gas, burned in solid oxide fuel cell 125kWe, future | Alloc Rec, U	No

Nuclear

Generation 2 and 3

Pressurised Water Reactors (PWR) were modelled using the available process in ecoinvent, as around 55% of the operative nuclear plants in EU 28 today are of this type (WNA 2017). The dataset in ecoinvent does not depend on efficiency, and therefore it was decided to extrapolate the efficiency from somewhere else, i.e. taking the average between U.S. EIA, 2015 (33%) and Leverenz et al., 2004 (36-37%) and retrieve the coefficients as usual (C2/efficiency) (the efficiency is kept constant for every country). In the process 92% of the nuclear fuel is enriched uranium which has LHV of 3900 GJ/kg (WNA 2016). As the LHV refers to uranium enriched at 3.5%, it seems more appropriate, as nuclear fuel input in ecoinvent is for uranium enriched at 3.8% (the closest).

Inputs/outputs for all countries are the same except for DE and FR, which have different emissions.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {*X*}| electricity production, nuclear, pressure water reactor | Conseq, U	No

Generation 4

A very-high-temperature reactor (VHTR) is the most viable reactor type in the near future. According to (OECD Nuclear Energy Agency 2014), the main (environmental) milestones for generation 4 reactors are the reduction of uranium (or other nuclear fuel) resource use and reduction of waste production. These should be considered, but no specific targets are set for these reductions. It was assumed that these changes are reflected in the efficiency data provided by TIMES panEU. Capital inputs will also change but this is more difficult to model (e.g. use of new coolant materials). Therefore, the dataset is essentially a copy of generation 2/3.

Waste non-renewable + Industrial waste

As the composition of the non-renewable/industrial waste was not known, it was assumed to be the same as municipal solid waste, so for every technology a copy of the relative process for municipal waste was created. The only difference is in the efficiencies given by TIMES PanEU.

Steam turbine + ORC

A copy of the municipal waste, steam turbine process was made and the waste incineration facility was replaced with the closest available process in ecoinvent for the ORC steam cycle (*Heat and power co-generation unit, organic Rankine cycle, 1000kW electrical {GLO}| construction | Conseq, U*).

Steam turbine with CCS Oxyfuel

A copy of the municipal waste, steam turbine CCS Oxyfuel process. No ORC was assumed here, but the conventional municipal waste incineration facility was kept.

IGCC

A copy of municipal waste, IGCC process.

Biomass solid / waste renewable

Municipal solid waste, steam turbine

A process for Denmark is available in ecoinvent, but it is scaled to the service of incinerating 1 kg of waste and not to the production of 1 kWh of electricity from waste. In addition, incineration of 1 kg of waste delivers both electricity and heat as by-products. Therefore, it was decided to use energy allocation keys to first obtain an incineration process that delivers only electricity and then create a process where the reference output product is electricity.

Energy allocation: in ecoinvent 1 kg of waste is reported to generate 1.39MJ electricity and 2.85 MJ heat, meaning that 33% of the total energy generated by 1 kg waste (4.24 MJ/kg) delivers electricity (and 67% heat), so 33% of the environmental burdens and inputs can be ascribed to electricity production. After obtaining a process where 1 kg waste produces only electricity (0.39 kWh), a new process producing 1 kWh electricity is created by rescaling every input/output.

In the original process, inputs/outputs do not depend on the efficiency, so it was modelled, as was done for hard coal, by assuming that the relation with the efficiency is the same (C2/efficiency). Crediting of recovered iron scrap was done (as avoided product).

Original process used from ecoinvent 3.3	**Process available for Denmark**
Municipal solid waste {DK}| treatment of, incineration | Conseq, U	Yes

Wood, steam turbine

A process for electricity production from wood chips in an organic Rankine cycle (ORC) steam generator is available for DK, but only for cogeneration. The allocation-based process was taken as done for natural gas, fuel cell, where available allocation based processes were replaced with consequential ones. Taking this process means assuming that the capital inputs and efficiency of an organic Rankine cycle (ORC) steam generator are similar to the steam turbine. The process is not present in the ecoinvent web database, but there was the analogous for heat generation, where electrical (15%) and thermal (45%) efficiencies are indicated and used (to calculate C2) even though entries in the dataset for heat do not depend on efficiency.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Alloc Rec, U	Yes

Municipal waste, steam turbine with CCS

A copy of the municipal waste, steam turbine process with CCS technology modifications was made. As no specification was given from TIMES PanEU model, it was assumed that the CCS technology is Oxyfuel as suggested in (Zeman 2010). The biogenic CO2 is also captured and stored (together with the fossil CO2). CO2 capture efficiency is 100% (Zeman 2010). For variation of emissions the same values as for hard coal were used.

Wood, steam turbine with CCS

A copy of the wood, steam turbine process with CCS technology modifications was made. As no specification is given from TIMES PanEU model, it was assumed that the CCS technology is Post-comb as it is the most mature technology (Al-Qayim et al. 2015). CO2 capture efficiency is 90% (Al-Qayim et al. 2015). For variation of emissions the same values as for hard coal were used.

IGCC, municipal waste

Copy of municipal waste, steam turbine.

IGCC, wood

Copy of wood, steam turbine.

Biogas

In ecoinvent only cogeneration processes are available for biogas, so to reduce the potential inaccuracy of choosing a cogeneration process it was decided to make copies of the corresponding processes for natural gas (for each technology type except fuel cell) and adjust the input of biogas (based on its LHV). However, emissions were still retrieved from the (allocation-based) cogeneration processes for biogas according to the type of technology (with some assumptions as described in the sections below). Efficiencies to calculate C2 were chosen according to the type of technology rather than the type of fuel, i.e. from biogas, when the corresponding technology is available in ecoinvent, otherwise from natural gas processes. Entries are set dependent on the efficiency as done for hard coal. LHV of biogas is retrieved from ecoinvent and kept constant for each technology type.

Steam turbine, gas turbine and combined cycle

As no processes for biogas-steam turbine, biogas-gas turbine and biogas-combined cycle are available, emissions are taken from the gas engine (internal combustion) process for biogas. The efficiency is instead kept the same as the one used in the natural gas process (in accordance with the type of technology).

Original process used to retrieve emissions (from ecoinvent 3.3)	Process available for Denmark
Electricity, high voltage {DK}| heat and power co-generation, biogas, gas engine | Alloc Rec, U	Yes

Internal combustion

Both emissions and efficiency (37% electric efficiency) are taken from the corresponding process for biogas.

Original process used from ecoinvent 3.3	Process available for Denmark
Electricity, high voltage {DK}| heat and power co-generation, biogas, gas engine | Alloc Rec, U	Yes

Fuel cell

The corresponding process for biogas available in ecoinvent is used, which is cogeneration and for Switzerland only. When available, allocation based processes were replaced with consequential ones. The efficiency given in ecoinvent for a fuel cell (0.47%) is used to calculate C2. LHV is not used, as input of methane in ecoinvent is only reported in MJ and, to avoid rescaling everything to m^3, input of biogas is calculated as C2/efficiency as for the rest of the entries.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, low voltage {CH}| biogas, burned in solid oxide fuel cell 125kWe, future | Alloc Rec, U	No

Hydro

A process exists for all three types of technology in ecoinvent (run-of-river, dam storage and pump storage). The amount of infrastructure ($Flow_{infrastructure}$) depends on plant lifetime (L) (taken from ecoinvent) and net annual electricity production (P_{net}) (which is provided by TIMES panEU), through the equation:

$$Flow_{infrastructure} = \frac{1}{L * P_{net}} \qquad \text{(B1)}$$

By using this relation, the amount of infrastructure becomes a parameter that changes in time. All the other inputs or emissions of a process are kept constant with time, and this is considered to be a fair assumption as for this type of technology (renewable energy) the infrastructure is most likely the most contributing process to environmental impacts.

Run-of-river

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {DK}| electricity production, hydro, run-of-river | Conseq, U	Yes

Dam storage

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {*X*}| electricity production, hydro, reservoir, non-alpine region | Conseq, U	No

Pump storage

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {*X*}| electricity production, hydro, pumped storage | Conseq, U	No

Wind

Onshore

A process for Denmark is available in ecoinvent. The inputs from the technosphere depend on several parameters: 1) installed capacity, 2) net electricity production (as 'gross electricity*(1-losses)'), 3) electrical output (or size) of the turbine (as 'capacity_MW') and 4) lifetime of the turbines (for the specific formulas see corresponding excel spreadsheet). Electrical output and lifetime are kept constant with time, whereas installed capacity and electricity production are linked to TIMES panEU data, therefore changing with time. The total capacity is fulfilled with turbines of different electrical output (or size). In 2005, 51% of the existing turbines was 0.5-1 MW, but modern wind turbines manufactured in Denmark had a capacity of 3 MW or more (Danish Energy Agency 2009). It is assumed that the total onshore capacity is achieved by turbines with an electrical output >3 MW (4.5 MW) until 2050.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {DK}| electricity production, wind, >3MW turbine, onshore | Conseq, U	Yes

Offshore

In the available process for Denmark infrastructure depends on lifetime and net energy production as in eq. 5. Lifetime is taken from ecoinvent and kept constant, whereas net energy production is taken from TIMES panEU data. The remaining inputs/waste flows are not changed and kept constant.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Electricity, high voltage {DK}| electricity production, wind, 1-3MW turbine, offshore | Conseq, U	Yes

Solar

Roof panel

A process for Denmark is available in ecoinvent. Single Si is chosen as it is more efficient than multi Si panels (Jungbluth and Stucki 2012). The infrastructure depends on the capacity of the panels, plant lifetime and specific yield of the panels. However, it is decided to relate the change (until 2050) in infrastructure needs to the change in efficiency, rather than the specific yield of the plant because data on efficiencies are more easily available. Data from TIMES panEU cannot be used to extrapolate efficiency (renewable energy technologies in TIMES panEU are modelled with an efficiency of 100%), therefore they are retrieved from somewhere else. Evolution of efficiency from 2015 to 2050 is calculated using data on large (> 800 cm2) monocrystalline Si panels from various articles published by Green et al. between 2007 to 2017 (Green et al., 2007; Green et al., 2015; Green et al., 2017). An average annual efficiency increase rate between years 2007 – 2017 has been calculated and used assuming that this rate will remain the same until 2050. Then the amount of infrastructure in certain year X ($Flow_{\text{infrastructure, year X}}$) is calculated as follows:

$$Flow_{infrastructure,\ year\ X} = no.pieces_{ecoinvent} * \left(\frac{efficiency_{2015}}{efficiency_{year\ X}}\right) \qquad \text{(B2)}$$

where, *no. pieces*$_{ecoinvent}$ is the amount of infrastructure in the original process from ecoinvent and *efficiency*$_{2015}$ is 22.4% (Green et al., 2015).

Original process used from ecoinvent 3.3	Process available for Denmark
Electricity, low voltage {DK}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Conseq, U	Yes

Plant size

A process for solar park is available in ecoinvent. The model follows the one for roof panels.

Original process used from ecoinvent 3.3	Process available for Denmark
Electricity, low voltage {*X*}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Conseq, U	No

Thermal

This technology corresponds to Concentrated Solar Power CSP (mirror or lenses concentrate light). Parabolic troughs are among the most used and mature technologies (IEA 2014). A process exists for Switzerland on heat production from solar collector system installed at family or multi-dwelling level, but the technology seems quite different from parabolic troughs (evacuated tube collector and Cu flat plate) in terms of materials and also because the technology is used to produce heat and not electricity. Therefore it is decided to assume this process as proxy (keeping the solar energy input and the electricity requirements), but it is converted to production of 1kWh electricity and a new process for the parabolic trough infrastructure is created following the data provided in (Piemonte et al. 2011) (see excel spreadsheet for more precise info and comments on data sources).

The efficiency improvements until 2050 are obtained by calculating the annual average improvement obtained between 1989 and 2010 (according to available sources (NREL 2003) (IEA 2010)) and assuming that the rate remains the same until 2050.

Original process used from ecoinvent 3.3	Process available for Denmark
Heat, central or small-scale, other than natural gas {CH}| operation, solar collector system, evacuated tube collector, one-family house, for combined system | Conseq, U	No

Geothermal

Only a process for a conventional plant is available in ecoinvent. Again, the entries in ecoinvent do not depend on efficiency, so it is decided to calculate the amount of infrastructure as in eq. B2 and keep the other flows constant in time. For both steam turbine and hot dry rock, closed loops of geothermal/fresh water use are assumed (fluids are re-injected), therefore gaseous emissions of CO_2, H_2S and mercury can be considered almost zero (Sigfusson and Uihlein 2015).

Steam turbine

The efficiency and the evolution hereof until 2050 is provided in Sigfusson and Uihlein, 2015. It is assumed that future plants will be binary cycle plants with Organic Rankine Cycle, which are suitable for the relatively low water temperature available in Denmark (Røgen et al., 2015; Sigfusson and Uihlein, 2015).

Original process used from ecoinvent 3.3	Process available for Denmark
Electricity, high voltage {AT}| electricity production, deep geothermal | Conseq, U	No (datasets for the various counties are identical, therefore AT is taken as proxy)

Hot dry rock

Hot dry rock exploits the heat of the rock to warm up water or a fluid that is circulated into the ground, so it can be assumed the same technology as for the steam turbine, but there is water or another fluid consumption and related emissions. However, no documentation is found on the amount of water/fluid needed and emissions, therefore the process for the steam turbine is copied. The efficiency and the improvement hereof until 2050 is provided in Sigfusson and Uihlein, 2015 (under Enhanced Geothermal Systems).

Ocean

Tidal

No process for ocean energy technology is available in ecoinvent. Tidal technology is similar in principle to hydro power plants run-of-river, therefore this process is chosen and modified to better resemble tidal technology: land transformations are removed; land occupation is substituted with sea-ocean occupation; water consumption and emissions are removed. Infrastructure amounts are calculated using eq. 6, so they depend on efficiency. However, in the literature efficiency is found only in terms of ‘capacity factor’ (capacity factor: ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over the same amount of time). So the capacity factor is used in the place of efficiency. Data on development of capacity factor until 2050 for tidal energy is provided in (Sgobbi et al. 2016).

Wave

Wave power could theoretically be somewhat similar to wind turbines, therefore the process for offshore wind power is taken and only efficiency, i.e. capacity factor is modified. It is assumed that capacity factor development for wave is the same as the one for tidal.

Hydrogen fuel cell

The ecoinvent process for Polymer Electrolyte Membrane Fuel Cell (PEM FC) is used, as this process uses mainly hydrogen as fuel, whereas solid oxide FC use hydrogen only at demonstration level (IEA, 2015; Das et al., 2017). The process is modelled as done for the biogas and natural gas fuel cell, i.e. with calculation of C2, use of LHV and efficiencies provided by TIMES PanEU, shift from Swiss-allocation-based to Danish-consequential-based processes (where possible). Regarding the process for hydrogen fuel production, in ecoinvent processes exist for liquid hydrogen production from fossil sources, from chlor-alkali electrolysis and other processes. Today hydrogen is mostly produced from natural gas (or fossil fuels in general) and only a small fraction from chlor-alkali electrolysis (Pehnt, 2003), therefore the process for hydrogen production from cracking of fossil fuels is used. Efficiency for calculation of C2 is taken from IEA, 2015, as it refers to hydrogen PEM FC (and not natural gas as in ecoinvent). However, all emissions (intended as exhaust emissions) are deleted (as done also in Pehnt, 2003).

Original process used from ecoinvent 3.3	Process available for Denmark
Electricity, low voltage {CH}| natural gas, burned in polymer electrolyte membrane fuel cell 2kWe, future | Alloc Rec, U	No

Electricity storage

Batteries

Different types of batteries are available in ecoinvent and it is decided to use lithium-ion batteries as they have the greatest potential for future development (Divya and Østergaard 2009). To convert to kWh of electricity output, gravimetric energy density of the batteries (Wh/kg) is used, which can be modelled as a parameter changing with time. The development of this parameter between 1990 and 2015 is calculated from (Loeffler et al. 2015) and (Crabtree et al. 2015). It is assumed that until 2050 the development will follow the same trend. So, the only parameter that changes with time is the amount of batteries needed to provide 1 kWh of electricity.

Original process used from ecoinvent 3.3	Process available for Denmark
Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Conseq, U	Not relevant

CAES (Compressed Air Energy Storage)

There is no process for CAES available in ecoinvent. A new process is created containing only an input of plant infrastructure and an auxiliary input of natural gas, which is needed (together with the compressed air) to run the gas turbine for electricity generation. The plant infrastructure is modelled as found in (Bouman et al. 2016), which provides a detailed inventory of materials and energy requirements (more details are found in the corresponding spreadsheet in 'created processes' sheet). The amount of infrastructure needed is calculated using the annual electricity production (provided by TIMES panEU), lifetime of the plant (30 years, Luo and Wang, 2013) and cycle efficiency. In Luo and Wang, 2013 some prospects in the development of the cycle efficiency until 2030 (increase of 10% between 2020 and 2030) are provided and this data is used (however it is assumed that it will not exceed 95%). The natural gas input is calculated from (Greenblatt et al. 2007) and is parameterized in time by multiplying by the ratio between the efficiency of the gas in 2015 and the efficiency in the selected year. Emissions from CAES operation are not included.

Vehicle storage

Electric vehicles are included only in the transport section and not as electricity storage mean, to avoid double counting.

Issues in technology models

For some technologies, allocation-based cogeneration processes have been used to model conventional power plants (and cogeneration efficiencies were used to calculate C2), due to lack of a suitable process in ecoinvent. This was done for the following technologies:

- Natural gas, fuel cell
- Municipal solid waste, all technologies (started from consequential-based process and performed allocation)
- Wood, all technologies
- Biogas, fuel cell. For the other technologies only emissions (and efficiency) are taken from allocation-based process
- Hydrogen fuel cell

Heat and electricity from Cogeneration Heat and Power plants (CHP)

General structure of the model

Table B6. List of CHP plants and modelling approach for both heat and electricity production processes.

Coal	**Modelling approach**	**Available for DK**
Steam Turbine	Available process in ecoinvent	Yes
Steam Turbine CO2 Seq.Oxyfuel	Copy of steam turbine with CCS modifications	
IGCC CO2 Seq.	Copy of steam turbine with CCS modifications	
Lignite		
Steam Turbine	Available process in ecoinvent	No
Steam Turbine CO2 Seq.Oxyfuel	Copy of steam turbine with CCS modifications	
IGCC CO2 Seq.	Copy of steam turbine with CCS modifications	
Oil		
Steam Turbine	Available process in ecoinvent	Yes
Gas Turbine	Copy of steam turbine	
Combined Cycle	Copy of steam turbine	
Internal Combustion	Copy of steam turbine	
Natural gas/non renewables		
Steam Turbine	Available process in ecoinvent	Yes
Gas Turbine	Copy of corresponding conventional electricity PP process	
Combined Cycle	Available process in ecoinvent	Yes
Combined Cycle CO2 Seq. Pre-Comb.	Copy of combined cycle with CCS modifications	
Internal Combustion	Copy of steam turbine	
Fuel Cell	Available process in ecoinvent	No (CH)

Nuclear		
Generation 2 and 3	Copy of corresponding conventional electricity PP process	
Waste non-renewable + Industrial Waste Heat		
Steam Turbine + ORC	Copy of municipal waste, steam turbine	
Biomass solid / Waste ren.		
Municipal Waste, steam turbine	Copy of corresponding conventional electricity PP process	
Wood, steam turbine	Available process in ecoinvent	Yes
Wood, IGCC	Copy of steam turbine	
Biogas / Biofuel		
Steam Turbine	Copy of internal combustion	
Internal Combustion	Available process in ecoinvent	Yes
Fuel Cell	Available process in ecoinvent	No (CH)
Geothermal		
Hot Dry Rock	Copy of corresponding conventional electricity PP process	
Hydrogen		
Fuel Cell	Copy of corresponding conventional electricity PP process	

Heat from CHP

Hard coal

Steam turbine

The available allocation-based ecoinvent process is used to calculate the coefficient C2 as done for the conventional PP. Efficiency to calculate C2 is taken from (Energinet.dk and Danish Energy Agency 2012), which is specific for Denmark (efficiency from ecoinvent was not used as the total efficiency of CHP plant was found to be too low (around 50-60%) compared to typical values (70-95%, (Nuorkivi 2010)) and heat and electricity production had same efficiencies).

To calculate heat and electricity efficiencies the following formulas were used (Energinet.dk and Danish Energy Agency 2012):

$$\eta_{e,MC} = \eta_{e,c} * \left\{1 - \frac{c_v}{c_b + c_v} * \frac{Q_{MC}}{Q_B}\right\} \; (B3)$$

for electricity efficiency, and:

$$\eta_{q,MC} = \frac{\eta_{e,c}}{c_b + c_v} * \frac{Q_{MC}}{Q_B} \; (B4)$$

for heat efficiency, where:

$\eta_{e,\,MC}$ is electric efficiency at minimum low-pressure condensation;
$\eta_{q,\,MC}$ is heat efficiency at minimum low-pressure condensation;
$\eta_{e,c}$ is electricity efficiency in full condensation mode;
c_v is loss of electricity generation per unit of heat generated at fixed fuel input; assumed constant;
c_b is back-pressure coefficient (electricity divided by heat); assumed constant;
Q_{MC} is heat capacity at minimum low-pressure condensation;
Q_B is heat capacity in full back-pressure mode (no low-pressure condensation)

All parameters are given in the same report from (Energinet.dk and Danish Energy Agency 2012). The formulas calculate the efficiency at minimum low-pressure condensation, which is an operating condition of the plant between the full condensation mode (no heat use) and the back pressure mode (all heat is used for heating purposes) (see also Eurelectric, 2002).

Emissions of ammonia and inputs of Selexol (in IGCC with CCS) have been allocated according to the heat and electricity efficiencies.

Original process used from ecoinvent 3.3	**Process available for Denmark**
Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, hard coal | Alloc Rec, U	Yes

Lignite

Steam turbine

Heat (and electric) efficiency for lignite cogeneration is assumed to be the same as the one used for hard coal from (Energinet.dk and Danish Energy Agency 2012).

Original process used from ecoinvent 3.3	**Process available for Denmark**
Heat, district or industrial, other than natural gas {*X*}| heat and power co-generation, lignite | Alloc Rec, U	No

Oil

Steam turbine

(Energinet.dk and Danish Energy Agency 2012) does not provide specific info on oil-fired steam turbine CHP plants efficiencies, and the efficiencies from hard coal, steam turbine CHP plant are therefore used.

Original process used from ecoinvent 3.3	Process available for Denmark
Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, oil | Alloc Rec, U	Yes

Gas turbine, combined cycle and internal combustion

The same efficiency as for hard coal, steam turbine CHP is used, as no technology- and fuel-specific efficiencies are found. But this is considered acceptable since it is only used for the calculation of C2.

Natural gas

Steam turbine

Efficiency to calculate C2 is taken from TIMES PanEU.

Original process used from ecoinvent 3.3	Process available for Denmark
Heat, district or industrial, natural gas {DK}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Rec, U	Yes

Combined cycle

Efficiency to calculate C2 is taken from TIMES PanEU.

Original process used from ecoinvent 3.3	Process available for Denmark
Heat, district or industrial, natural gas {DK}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Alloc Rec, U	Yes

Fuel cell

Efficiency to calculate C2 is taken from (Energinet.dk and Danish Energy Agency 2012) (for continuous power generation plant at full load).

Original process used from ecoinvent 3.3	Process available for Denmark
Heat, future {CH}| natural gas, burned in solid oxide fuel cell 125kWe, future | Alloc Rec, U	No

Biomass solid / waste ren.

Wood, steam turbine

Efficiency to calculate C2 is taken from ecoinvent.

Original process used from ecoinvent 3.3	Process available for Denmark
Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Alloc Rec, U	Yes

Biogas

Internal combustion

Efficiency to calculate C2 is taken from TIMES panEU.

Original process used from ecoinvent 3.3	Process available for Denmark
Heat, central or small-scale, other than natural gas {DK}| heat and power co-generation, biogas, gas engine | Alloc Rec, U	Yes

Fuel cell

Efficiency to calculate C2 is taken from ecoinvent.

Original process used from ecoinvent 3.3	Process available for Denmark
Heat, future {CH}| biogas, burned in solid oxide fuel cell 125kWe, future | Alloc Rec, U	No

Electricity from CHP

The same approach used to model heat production from CHP is used also here. The corresponding processes for electricity production from CHP available in ecoinvent are showed in Table 9.

Table B7. List of the processes from ecoinvent used to model electricity from CHP plants.

Technology	Original process used from ecoinvent 3.3	Process available for Denmark
Hard coal, steam turbine	Electricity, high voltage {DK}| heat and power co-generation, hard coal | Alloc Rec, U	Yes
Lignite, steam turbine	Electricity, high voltage {X}| heat and power co-generation, lignite | Alloc Rec, U	No

Oil, steam turbine	Electricity, high voltage {DK}| heat and power co-generation, oil | Alloc Rec, U	Yes
Natural gas, steam turbine	Electricity, high voltage {DK}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Rec, U	Yes
Natural gas, combined cycle	Electricity, high voltage {DK}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Alloc Rec, U	Yes
Natural gas, fuel cell	Electricity, low voltage {CH}| natural gas, burned in solid oxide fuel cell 125kWe, future | Alloc Rec, U	No
Wood, steam turbine	Electricity, high voltage {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Alloc Rec, U	Yes
Biogas, internal combustion	Electricity, high voltage {DK}| heat and power co-generation, biogas, gas engine | Alloc Rec, U	Yes
Biogas, fuel cell	Electricity, low voltage {CH}| biogas, burned in solid oxide fuel cell 125kWe, future | Alloc Rec, U	No

Transport

General considerations

Biofuels are not modelled in SimaPro, so no blending of fuels is considered. Therefore, when using data on total fuel consumption the input from the biofuels is included (in terms of kg consumed per pkm/tkm), but their production is not modelled, so the total consumption of energy for transport comes only from conventional fuels (typically fossil fuels) and emissions are relative to combustion of only that fuel. For example, for diesel car, only diesel is considered (modelled), and associated with the total fuel consumption (i.e. including also biodiesel, bio FT diesel, etc.). Processes for bioethanol and biodiesel vehicles are created in Simapro, but emissions are missing.

Passenger cars

Table B8: Types of vehicles modelled for passenger cars.

ICEV= Internal Combustion Engine Vehicle
HEV= Hybrid Electric Vehicle
PHEV= Plug-in Hybrid Electric Vehicle
BEV= Battery Electric Vehicle
LPG= Liquefied Petroleum Gas
DME= Dimethyl Ether

FT-diesel= synthetic Fischer-Tropsch diesel

Type of vehicle from TIMES panEU data	**Modelled type of vehicle**
Diesel	ICEV
D, Diesel	
D, Biodiesel	
D, Bio FT-Diesel	
D, Fossil FT-Diesel	
Diesel hybrid	HEV
DH, Diesel	
DH, Biodiesel	
DH, Bio FT-Diesel	
DH, Fossil FT-Diesel	
Diesel PHEV	PHEV
DP, Electricity	
DP, Diesel	
DP, Biodiesel	
DP, Bio FT-Diesel	
DP, Fossil FT-Diesel	
Gasoline	ICEV
G, Gasoline	
G, Ethanol	
Gasoline hybrid	HEV
GH, Gasoline	
GH, Ethanol	
Gasoline PHEV	PHEV
GP, Electricity	
GP, Gasoline	
GP, Ethanol	
Natural Gas	ICEV
NG, Natural Gas	
NG, Biogas	

Natural Gas hybrid	HEV
NGH, Natural Gas	
NGH, Biogas	
Natural Gas PHEV	PHEV
NGP, Electricity	
NGP, Natural Gas	
NGP, Biogas	
Ethanol	ICEV
Ethanol hybrid	HEV
Ethanol PHEV	PHEV
EP, Electricity	
EP, Ethanol	
Biodiesel	ICEV
LPG	ICEV
DME	ICEV
Fossil DME	
Bio DME	
Combined Combustion	ICEV
CC, Bio FT-Diesel	
CC, Fossil FT-Diesel	
Methanol IC	ICEV
Fossil Methanol	
Bio Methanol	
Methanol FC	Fuel cell vehicle
Electricity	BEV
Hydrogen IC	ICEV
Hydrogen FC	Fuel cell vehicle
Hydrogen FC hybrid	Fuel cell HEV

Internal Combustion Engine Vehicles (ICEV)

If available, the corresponding process in ecoinvent is used based on the type of fuel. When not available, the closest technology is assumed (Table 11). Inputs from the technosphere and waste outputs in ecoinvent depend on several parameters (see equations in excel spreadsheet 'cars'), some of them constant (Table 12) and some changing with time (fuel consumption and vehicle weight). ICEV weight is assumed as done in (Bohnes et al. 2017), i.e. calculated average ICE weight in Denmark in the last 5 years from (ICCT 2015). Emissions are typically calculated by multiplying a coefficient (or emission factor) by the total fuel consumption. Not all the emissions are calculated in this way in ecoinvent, but it is assumed they are and coefficients are calculated back using the total emission of a certain compound and the fuel consumption used in the ecoinvent dataset.

Table B9. Original processes used for ICE vehicles.

Fuel	Original process used from ecoinvent 3.3
Diesel	Transport, passenger car, medium size, diesel, EURO 5 {RER}| transport, passenger car, medium size, diesel, EURO 5 | Conseq, U'
Gasoline	Transport, passenger car, medium size, petrol, EURO 5 {RER}| transport, passenger car, medium size, petrol, EURO 5 | Conseq, U
Natural gas	Transport, passenger car, medium size, natural gas, EURO 5 {RER}| transport, passenger car, medium size, natural gas, EURO 5 | Conseq, U
Ethanol	Assumed the same as gasoline
Biodiesel	Assumed the same as diesel
LPG	Transport, passenger car, medium size, liquefied petroleum gas, EURO 5 {GLO}| transport, passenger car, medium size, liquefied petroleum gas (LPG), EURO 5 | Conseq, U
DME	Assumed the same as diesel
Combined combustion	Assumed the same as diesel
Methanol IC	Assumed the same as gasoline
Hydrogen IC	Assumed the same as gasoline

Table B10. Constant parameters used for ICEV.

Constant parameters	Value	Unit	Source
Brake wear emissions	4.45E-09	kg/kg vehicle	ecoinvent
Vehicle lifetime	150000	km	ecoinvent
Road wear emissions	9.79E-09	kg/kg vehicle	ecoinvent

Tyre wear emissions	5.73E-08	kg/kg vehicle	ecoinvent
Scaling factor	1.29E+00	dimensionless	ecoinvent
SO_2 emission factor	2.00E-05 (diesel, gasoline) 2.03E-05 (natural gas)	kg/kg fuel	ecoinvent
CO_2 emission factor	3.14E+00 (diesel) 3.18E+00 (gasoline) 2.01E+00 (natural gas)	kg/kg fuel	ecoinvent
Average load	97.2	kg	ecoinvent

Hybrid Electric Vehicles (HEV)

HEV are modelled as done in (Bohnes et al. 2017): depending on the type of fuel, the corresponding process modelled for ICE vehicles is taken and modified to represent a hybrid car, by replacing the ICE car with electric car, adding the battery and the internal combustion engine. As in ICE vehicles, inputs from technosphere and waste outputs in ecoinvent depend on constant parameters (Tables 12 and 13) and parameters changing with time (fuel consumption and vehicle weight). Formulas on how to calculate entries are taken from a dataset for an electric car (see equations in excel spreadsheet 'cars'). To calculate amount of internal combustion engine, the powertrain weight (from ICEV production dataset) is divided by the weight of the hybrid car (battery plus electric car) and multiplied by the inputs of electric car and battery per pkm. HEV weight is taken from (Bohnes et al. 2017). Development of battery weight until 2050 is calculated using development of battery density and capacity as in (Bohnes et al. 2017). It is assumed that baseline emissions of a conventional diesel car and a diesel hybrid are the same, as the fuel needs to be burned anyway to charge the battery. Therefore, emissions factors are taken from ICE vehicles.

Table B11.

Constant parameters	**Value**	**Unit**	**Source**
Battery lifetime	1.00E+05	km	ecoinvent
Battery density 2015	1.14E-01	kWh/kg	ecoinvent
Battery density 2020	2.35E-01	kWh/kg	(USABC 2013)
Battery capacity 2015	2.35E+01	kWh	(Garcia et al. 2015)
Battery capacity 2020	4.50E+01	kWh	(Garcia et al. 2015)
Brake wear scaling factor	2.00E-01	Dimensionless	ecoinvent
Powertrain weight	4.01E+02 (diesel car) 3.21E+02 (gasoline and natural gas car)	kg	ecoinvent

Plug-in Hybrid Electric Vehicles (PHEV)

The model for PHEV is built in the same way as HEV, except for vehicle and battery weights (which are both taken from (Bohnes et al. 2017), the additional input of electricity from grid and of course fuel consumption from TIMES PanEU.

BEV

Modelled as in (Bohnes et al. 2017).

Original process used from ecoinvent 3.3	Process available for Denmark
Transport, passenger car, electric {GLO}| processing | Conseq, U	No

Fuel cell vehicles

The vehicle is modelled according to (Bohnes et al. 2017). An inventory for a fuel cell vehicle is taken from (Simons and Bauer 2015). The weight of the fuel cell component is assumed to decrease over time according to (Simons and Bauer 2015), which refers to U.S. future targets (no similar targets could be found for Europe). So specific mass is assumed to be 2.75 kg/kW in 2015 and 1.55 in 2020 and to remain constant until 2050. To calculate the amount of fuel cell needed per pkm the inventory data for fuel cell in (Simons and Bauer 2015) is given per kW of stack, so they are divided by the specific mass of the stack to obtain data per kg of stack. Therefore, the process for production of fuel cell is scaled per kg stack.

Fuel cell hybrid vehicles

The model is a copy of fuel cell vehicles, with the addition of the battery as in HEV.

Biofuels and alternative fuels production

Table B12. Processes used to model biofuels and alternative fuels production (all types of vehicle).

Fuel	Original process used from ecoinvent 3.3	Comment
Biodiesel	Vegetable oil methyl ester {GLO}| market for | Conseq, U’	Biodiesel produced from different feedstocks according to the country/region of origin: soybean, rapeseed and palm oil.
Ethanol	Ethanol, without water, in 99.7% solution state, from fermentation {GLO}| market for | Conseq, U	Ethanol produced from different feedstocks according to the country/region of origin: rye, whey, grass, sugar beet, sugarcane, maize, sweet sorghum, wood, potatoes.

Fossil DME	Dimethyl ether {GLO}| market for | Conseq, U	Fossil DME produced from methanol (derived from natural gas).
FT-diesel	Same as conventional diesel	No available process for FT-diesel in ecoinvent. It is assumed to be the same as conventional diesel.
Fossil methanol	Methanol {GLO}| market for | Conseq, U	Methanol produced from natural gas
Bio methanol	Methanol, from biomass {RoW}| market for | Conseq, U	Methanol derived from syngas obtained from gasification of wood
Fossil hydrogen	Hydrogen, liquid {RER}| market for | Conseq, U	Liquid hydrogen fuel produced from cracking of fossil fuels

Emissions from GREET

Table B13. Emission factors from GREET model used to model vehicles running on alternative fuels. Note that for methanol emission factors are available only if the fuel is used in fuel cell vehicle. Thus, for ICE vehicles running on methanol, the same factors are used as no other data is available.

		Fuel	DME from natural gas-derived methanol	Fossil FT diesel from natural gas	Fossil methanol from natural gas	Hydrogen from natural gas	
		Vehicle type	CIDI ICEV - DME	CIDI ICEV - FT diesel	FCV - MeOH	SI ICEV - liquid H2	FCV - liquid H2
Substance	**Unit**						
VOC	t/MJ		3.05E-08	3.05E-08	9.03E-09	6.22E-09	0
CO	t/MJ		7.45E-07	7.45E-07	1.98E-07	1.36E-07	0
NOx	t/MJ		3.49E-08	3.49E-08	8.51E-09	2.93E-08	0
PM10	t/MJ		0	1.47E-09	0	1.40E-10	0
PM2.5	t/MJ		0	8.78E-10	0	1.24E-10	0
CH4	t/MJ		6.58E-08	3.29E-08	6.09E-10	2.10E-10	0
CO2	t/MJ		6.48E-05	7.10E-05	6.81E-05	-2.34E-07	0

N2O	t/MJ	1.74E-10	1.74E-10	3.77E-10	1.30E-09	0
VOC urban	t/MJ	2.11E-08	2.11E-08	6.23E-09	4.29E-09	0
CO urban	t/MJ	5.14E-07	5.14E-07	1.36E-07	9.40E-08	0
NOx urban	t/MJ	2.41E-08	2.41E-08	5.87E-09	2.02E-08	0
PM10 urban	t/MJ	0	1.01E-09	0	9.68E-11	0
PM2.5 urban	t/MJ	0	6.06E-10	0	8.56E-11	0
CH4 urban	t/MJ	4.54E-08	2.27E-08	4.20E-10	1.45E-10	0
CO2 urban	t/MJ	4.47E-05	4.90E-05	4.70E-05	-1.61E-07	0
N2O urban	t/MJ	1.20E-10	1.20E-10	2.60E-10	8.96E-10	0
VOC evap.	t/MJ	0	0	1.57E-08	0	0
VOC evap. urban	t/MJ	0	0	1.08E-08	0	0

Heavy duty vehicles

Only diesel as fuel type and internal combustion engine is accessible in ecoinvent. i.e. there is only one process as starting point. The EURO6 emissions standard has been used. Coefficients were not obtainable from ecoinvent metadata, so the model has been made by dividing all the emissions to air by the fuel consumption given by ecoinvent and multiplying with the fuel consumption calculated from the TIMES-model (based on the assumption that emissions depend on fuel consumption pr tkm). The brake, tyre, and road emissions have been parameterised with regards to vehicle lifetime and gross vehicle weight, however these values are kept the same as those from ecoinvent. The same goes for the amount of lorry, maintenance, and road assigned pr tkm.

- **HDV is assumed to keep the same weight throughout the time period. The ecoinvent values of average load factor 15.96t and a gross vehicle weight (GVW) of 33.2t are used.**
- **The lifetime of HDV is assumed the same as in ecoinvent: 540,000 vkm**

Other fuel types

Diesel as fuel is the only process available in ecoinvent. To model other fuel types it is assumed that differences in emissions from cars stem from the difference in fuel type, hence that the ratio between the emission coefficients are the same also for HDV. Emission coefficients based on the following equation has been used:

$$HDV_{new,i} = \frac{car_{new,i}}{car_{diesel,i}} * HDV_{diesel,i} \ (B5)$$

i.e., the emission factors for each compound *i* for the new fuel type are calculated by multiplying the ratio between emission factors for cars with the emission factors for the diesel heavy duty vehicle.

Electric truck

For hybrid vehicles and plug-in hybrid electric vehicles an "electric lorry" process was made from the process for ICE vehicles and an electric powertrain was added. The amount needed is copied from "Passenger car, electric, without battery, GLO, production"; the unit is kg-powertrain/kg-vehicle, and it is assumed that this factor is the same for passenger cars and for HDV. The factor is multiplied by gross vehicle weight (kg-vehicle) to give a total powertrain weight of 2900kg

Hybrids

For hybrids, the fuel type is a copy of the pure-fuel process, where the conventional lorry is replaced with the electric lorry (described above), with the same battery process as for cars is added, NiMH (see table for name of process). The amount needed per tkm is similar to that of the passenger car, but divided by load.

Battery weight is upscaled from the value of 56kg from (Hosoya and Yamaguchi, 2007) for a LDV of average gross vehicle weight 5.5t; for GVW of 33.2t this becomes 332kg of battery.

Battery lifetime is not estimated by Hosoya and Yamaguchi, 2007, and is therefore assumed to be the same as for cars, 10,000 vkm.

Item	Process
Battery	Battery, NiMH, rechargeable, prismatic {GLO}| market for | Conseq, U

PHEVs

For PHEVs a Li-ion battery is added to a copy of the pure-fuel version with electric lorry replacing the conventional. The weight of the battery is assumed to be 5.5 times that of the hybrid battery, as this is the ratio between the battery weights for cars.

Fuel Cells

For HDV fuel cells a copy of the same fuel type process as for ICE vehicles was made, and the vehicle changed from conventional to electric. Hereto was added the same fuel cell process as for cars. The weight of the fuel cell is assumed to be 400kg, based on the two types, 80 and 150 kW, produced by US hybrid (U.S. Hybrid 2019). This weight is divided by the HDV lifetime and the load, to get the amount in tkm.

Light Duty Vehicles

LDVs have been modelled like the HDVs. The starting process is shown in the table.

	ecoinvent process
HDV	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | Conseq, U
LDV	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Conseq, U

The average gross vehicle weight assumed is 4984kg, average load of 0.98t, and lifetime 540000vkm, all as reported in ecoinvent.

Other fuel types have been modelled in the same way as for HDV.

The size of the truck used is 16 metric tonnes, which is too heavy for a LDV with GVW of ~5t. However, this is how it is modelled in ecoinvent, since no smaller truck is available – and it is the same truck used for HDV. Hence, the same electric lorry is used also for LDVs.

For hybrids a NiMH battery weight of 56 kg is used, for PHEVs no sources were found for Li-ion battery weight, so the same scaling factor as for cars is used; 5.5, giving a Li-ion battery weight of 308kg.

Fuel cell weight was estimated to be 150kg based on (U.S. Hybrid 2019) cells for medium and heavy duty vehicles of 248kg and 474kg, and weight of fuel cell for cars 110kg (2015) to 62kg (2020 onwards).

Buses

Three processes for bus transportation are available in ecoinvent. One is for coach, which is long distance, another is a regular bus (short distance), and the last is a trolley bus driving on electricity from overhead cables. The first two processes are more or less identical, having the exact same comment in the process description documentation in SimaPro, but different fuel efficiencies, and more or less the same emission coefficients (when fuel consumption per pkm is divided out of the emission). The regular bus is chosen as a starting point.

	Original process
Bus	Transport, regular bus {CH}| processing | Conseq, U

In SimaPro the amount of bus per pkm is 7.14E

The amount of bus (pieces) used per pkm is 7.14e-8. If the bus runs 2.39e5 vkm in its lifetime, then the average number of passengers must be $(7.14e\text{-}8 * 2.39e5)^{-1}$ = 58.58.

Road input has been kept at the value from ecoinvent, as the calculations behind could not be found or reconstructed.

For buses, there are no separate tyre, brake, and road wear emissions; it is assumed that these are included in the fuel emissions. Emissions to all compartments (soil, water and air) are parameterised with respect to fuel consumption.

Other fuel types

The approach is the same as for HDV and LDV.

The original process has emissions to soil and water (same values for metals to the two compartments), which the diesel car process does not have. To model these emissions, the ratio between emissions to air and to soil (or water) for the metal has been applied to the fuel type specific emission to obtain the emission to soil or water. If no emission is available for air, the corresponding emission to soil/water is deleted.

Electric bus

There is no process modelling an electric bus in ecoinvent. The same procedure as for the electric lorry has been followed; adding an up scaled powertrain (for passenger car) to the process.

Hybrid and PHEV

According to Volvo, they use Li-ion batteries for their hybrid buses; though they do not mention either capacity or weight, and modelled values are therefore based on assumptions. Both hybrids and PHEVs are modelled with Li-ion batteries.

Fuel cells

A smaller version than the fuel cell for HDV is assumed based on (U.S. Hybrid 2019).

Motorcycles

There is no process in ecoinvent for motorcycles. The USLCI database has a process for a gasoline-powered motorcycle, based on emissions from GREET. This has been used as a starting point.

The USLCI-process does not include the making of the motorcycle, and no process can be found for this. The gasoline-powered motorcycle and the maintenance of it has been up-scaled by a factor 1.2. The amount of road had been copied as is (not parameterised) from the electric motorcycle process. The USLCI inputs of transport by various means have been deleted. Gasoline and ethanol are added as each type of fuel, as emission coefficients are the same for the two fuel types.

	Original process
Gasoline	Transport, motorcycle, gasoline powered/personkm/RNA (USLCI)
Electric	Transport, passenger, electric scooter {GLO}| processing | Conseq, U

For the electric motorcycle the process for electric scooter has been used as a starting point and up-scaled by a factor 1.2 for both the scooter and maintenance of it.

Rail

Freight

The data from TIMES PanEU have an input of both diesel (of various origins) and electricity. There are processes specific to several European countries; the difference between them are the fuel efficiency (which depends on the country’s rail tracks, slopes, and the like) and the input of electricity; either of them can be used as a starting point. The chosen original process is shown in the table.

	Original process
Train, freight	Transport, freight train {CH}| electricity | Conseq, U

Fuel and electricity input is extracted from TIMES PanEU. The diesel mix is modelled as regular diesel, to be consistent with what is done for road vehicles. The electricity is chosen from the country specific grid mix, high voltage. The other inputs are left as they are, because it is not transparent how they were calculated by ecoinvent. Emissions are updated as with HDV; all are divided by the fuel efficiency of the original process and then multiplied by the fuel efficiency from TIMES. The only exception is sulfur hexafluoride, which is parameterised with regards to electricity according to the comment on emission in ecoinvent.

Passenger

The Swiss processes are all electric, i.e. no diesel used, and thus cannot be used as a starting point. There are processes specific to several European countries, “high speed” are only electric, “processing” use diesel and electricity. They all yield the same emission coefficients when the fuel efficiency is divided out. The German is chosen as starting point.

	Original process
Train, passenger	Transport, passenger train {DE}| processing | Conseq, U

Aviation

The data from TIMES panEU are separated into Domestic, intra-EU and extra-EU. The processes in ecoinvent are divided into intra- and intercontinental, which will cover the last two categories. Domestic is modelled as a copy of intra-EU, as this is the shorter distance, with only the fuel input different. In ecoinvent the processes are further divided into passenger and freight, but these have the same emission coefficients.

As no activity data is available for aviation, the process is different from the other transport processes: The output is not in pkm or tkm but in one “piece” of total aviation for the country. The input is the total fuel consumption (kg-fuel) for the country rather than the fuel efficiency (kg-fuel/pkm). All emissions have been divided with the fuel efficiency from ecoinvent and then multiplied with the fuel consumption from TIMES panEU. The same is done for input of aircraft and airport to obtain an estimate.

Only kerosene as used as fuel in ecoinvent, i.e. the emission coefficients are for kerosene. The TIMES panEU data also has input of gasoline and diesel; all three fuel types are used in the process for upstream impacts, and the total mass of fuel is used for emission impacts (i.e. as a proxy it is assumed that diesel and gasoline have the same emission coefficients as kerosene). Bio FT-Kerosene is also an input in TIMES panEU; it has been modelled as normal kerosene because there is no process in ecoinvent on bio kerosene.

	Original process
Domestic	(copy of intra-EU, only fuel input updated)
Intra-EU	Transport, passenger, aircraft {RER}| intracontinental | Conseq, U
Extra-EU	Transport, passenger, aircraft {RER}| intercontinental | Conseq, U

Navigation

The TIMES data is divided into “generic” and “bunkers”, each with fuel types Gasoline, Diesel, Oil. As for aviation, only data for fuel input are available, not the activity. The processes chosen as starting points are shown in the table. The process for bunkers originally used heavy fuel oil as fuel, so the emission coefficients are for this type – fuel types gasoline and diesel are added for upstream impacts, but the same emission coefficients as for oil are used. (as done for aviation).

	Original process
Generic	Transport, freight, inland waterways, barge {RER}| processing | Conseq, U
Bunker	Transport, freight, sea, transoceanic tanker {GLO}| processing | Conseq, U

Sectors

Coal

Coal is assumed to be mainly bituminous coal. However, there is no process in ecoinvent using specifically bituminous coal. It is assumed that coal burning in the various sectors is small scale, therefore the choice is between two small scale processes of 5-15kW (coke or briquettes) or one very crude process of 1-10MW. The small scale briquette process was assumed. Looking at the numbers in TIMES PanEU Base Pathway from July 2018 it can be observed that it is mainly the industry sector that uses coal, with agriculture using a minor amount, and household and commercial having zero use for all checked countries. Hence, for industry and agriculture the process with 1-10MW capacity is chosen. For residential and commercial the smaller process of 5-15kW is chosen.

Petroleum products - split

For each sector a mix of petroleum products based on (Eurostat 2019) is made. INDIC_NRG categories used to model each sector are shown in the table below, as are the product codes. The split has been calculated based on available data for each country; however, for some products nothing had been reported (marked with ":" in Eurostat) which means that this product will show up as "0" in our model. Switzerland is not listed in Eurostat, and a geometric mean of available data for the other countries is used. For agriculture in Germany only zeroes were reported (since 2000), and hence the geometric mean is also used in this case. The mix is not modelled to vary with time though it is known to do as the petroleum split cannot be extracted from TIMES. Categories have been selected based on processes available in Ecoinvent. Summary is shown in the table below and explained in the following sections.

Table B14.

	Agriculture	Commercial	Households	Industry
INDIC_NRG category	B_102030 Agriculture/ Forestry	B_102035 Services	B_102010 Residential	B_101800 Final Energy consumption - Industry

LPG *3220 Liquefied petroleum gas (LPG)*	LPG for sectors - jlm	LPG for sectors - jlm	LPG for sectors - jlm	LPG for sectors – jlm
Gasoline *3234 Gasoline (without bio component)*	Petrol, unleaded, burned in machinery {GLO}| petrol, unleaded, burned in machinery | Conseq, U	Petrol, unleaded, burned in machinery {GLO}| petrol, unleaded, burned in machinery | Conseq, U	Petrol, unleaded, burned in machinery {GLO}| petrol, unleaded, burned in machinery | Conseq, U	Petrol, unleaded, burned in machinery {GLO}| petrol, unleaded, burned in machinery | Conseq, U
Kerosene *3247 Kerosene type jet fuel (without bio component)*	-	-	-	Kerosene for industry – jlm
Diesel *3260 Gas/diesel oil (without bio component)*	Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Conseq, U	Heat production, diesel, boiler - jlm	Heat production, diesel, boiler - jlm	Diesel, burned in building machine {GLO}| processing | Conseq, U
Fuel oil *3270A Total fuel oil*	Heat production, light fuel oil, at boiler 100kW condensing, non-modulating {{DK}} | Conseq, U – jlm	Heat production, light fuel oil, at boiler 100kW condensing, non-modulating {{DK}} | Conseq, U – jlm	Heat production, light fuel oil, at boiler 100kW condensing, non-modulating {{DK}} | Conseq, U – jlm	Heat production, light fuel oil, at boiler 100kW condensing, non-modulating {{DK}} | Conseq, U – jlm
Coke *3285 Petroleum coke*	-	Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, hard coal coke, stove 5-15kW | Conseq, U	Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, hard coal coke, stove 5-15kW | Conseq, U	Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, hard coal coke, stove 5-15kW | Conseq, U

Other *3295 Other oil products*	-	Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, lignite briquette, at stove 5-15kW | Conseq, U	-	Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, lignite briquette, at stove 5-15kW | Conseq, U

LPG

Based on Ecoinvent process “Transport, passenger car, medium size, liquefied petroleum gas, EURO 5 {GLO}| transport, passenger car, medium size, liquefied petroleum gas (LPG), EURO 5 | Conseq, U” where everything but emissions and fuel has been removed. For converting to energy, the LHV of 46.607MJ/kg has been used.

Gasoline

The only ecoinvent process with gasoline [petrol] has been used.

Kerosene

Based on Ecoinvent process “Transport, passenger, aircraft {RER}| intracontinental | Conseq, U” with same procedure as for LPG.

Diesel

For agriculture and industry ecoinvent contained processes specific enough for these sectors. For household and commercial the most appropriate process “Heat production, light fuel oil, at boiler 100kW condensing, non-modulating {{DK}} | Conseq, U - jlm” has been adjusted by changing the fuel input from light fuel oil to diesel, correcting the amount of diesel used by multiplying the original quantity by LVH(light fuel oil)/LHV(diesel) but otherwise keeping the emissions as the same.

Fuel oil

Based on Ecoinvent process “Heat, central or small-scale, other than natural gas {RoW}| heat production, light fuel oil, at boiler 100kW condensing, non-modulating | Conseq, U” where the electricity input has been adjusted to the one from our model.

Coke

The chosen process from ecoinvent was deemed as the most fitting for this fuel input.

Other

It is not clear from Eurostat what this category contains. Lignite has been assumed as the most fitting process for this fuel type.

Gas

Gas is assumed to be natural gas. For households, a share of it is used for cooking (see later section). For heating, according to (Energinet.dk and Danish Energy Agency 2018), the common technology in Denmark is a modulating, condensing boiler with low-NOx technology. This is used both for Households and Commercial sector. For the agricultural sector, only the process related to heat is included.

The ecoinvent process "Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW | Conseq, U" has been used as a starting point, where the electricity input has been changed from default to the country specific mix in our model.

Electricity and heat

Electricity of high, medium, and low voltage is from the national grid mixed from the modelled production as described in the above section. Same with the heat mix.

Auto producers in Industry sector

Based on Eurostat categories for auto producers the six categories shown in the table below was selected. To obtain the split for auto producers, production numbers from the national grid (from TIMES) was used: the sum of electricity from power plants and electricity from combined heat and power plants for all six categories was used as the share of the technology, and the sum of PP and CHPP for the category was divided by this share. In this, it is assumed that auto producers only use technologies as the listed, and not e.g. nuclear, wind, or hydro.

To obtain the fuel type (and technology) split, the Eurostat database was used to retrieve data on auto producers. The (50+) categories were grouped as listed in the table below and matched to ecoinvent processes.

Table B15.

Grouping	Eurostat categories	Ecoinvent process used
PV	Photovoltaics	Electricity, low voltage {DK}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Conseq, U
Coal	Coking coal, other bituminous coal, sub-bituminous coal, lignite/brown coal, coal tar, BKB (brown coal briquette)	Electricity, high voltage {DE}| electricity production, hard coal | Conseq, U
Gas	Natural gas, gas works gas, coke oven gas, blast furnace gas, other recovered gas, refinery gas, LPG	Electricity, high voltage {CH}| electricity production, natural gas, combined cycle power plant | Conseq, U
Oil	Oil shale and oil sands, gas/diesel oil, residual fuel oil, other oil products, kerosene	Heavy fuel oil, burned in refinery furnace {Europe without Switzerland}| processing | Conseq, U
Waste	Industrial waste, municipal waste (renewable and non-renewable)	Electricity, for reuse in municipal waste incineration only {DK}| electricity, from municipal waste incineration to generic market for electricity, medium voltage | Conseq, U
Biogas/biofuel	Biogases	Electricity, high voltage {DK}| heat and power co-generation, biogas, gas engine | Conseq, U

For each grouping the numbers from the Eurostat categories were added and then divided by the sum of all categories, in order to get the fraction that the grouping contribute to the total. These fractions were entered into the Excel sheet linking to SimaPro, and the appropriate links made in SimaPro.

The group “other” is highly dominated by the “combustible fuels” categories which is why it has been approximated with a diesel burning process. It has not been possible to find metadata on Eurostat explaining what the different categories include, and hence the model has been built solely on the title of the category.

Renewables

Renewables have their own specific tables:

Table B16.

Energy carrier	Agriculture	Commercial	Households	Industry
Ambient Heat	---	Heat pump 30kW, allocation exergy - jlm	Heat pump 30kW, allocation exergy - jlm	Heat pump 30kW, allocation exergy - jlm
Biodiesel	Biodiesel, burned in agricultural machinery - jlm	Biodiesel, burned in diesel-electric generating set, 18.5kW - jlm	Biodiesel, burned in diesel-electric generating set, 18.5kW - jlm	---
Biogas	---	Biogas, burned in micro gas turbine 100kWe | Conseq, U - jlm	Biogas, burned in micro gas turbine 100kWe | Conseq, U - jlm	---
Biomass	Heat production, wood pellet, at furnace 300kW {{DK}} | Conseq, U - jlm	Heat production, wood pellet, at furnace 9kW {{DK}} | Conseq, U – jlm & Heat production, wood pellet, at furnace 300kW {{DK}} | Conseq, U - jlm	Heat production, wood pellet, at furnace 9kW {{DK}} | Conseq, U – jlm & Heat production, wood pellet, at furnace 300kW {{DK}} | Conseq, U - jlm	---
Biomas, Municipal Waste, bioliquid	---	---	---	Waste wood, untreated {CH}| treatment of, municipal incineration with fly ash extraction | Conseq, U & Biodiesel, burned in diesel-electric generating set, 18.5kW – jlm & Energy waste incineration {{DK}} - jlm

Geo-thermal	Electricity, high voltage {AT}| electricity production, deep geothermal | Conseq, U	Electricity, high voltage {AT}| electricity production, deep geothermal | Conseq, U	Electricity, high voltage {AT}| electricity production, deep geothermal | Conseq, U	Electricity, high voltage {AT}| electricity production, deep geothermal | Conseq, U
Solar	Electricity, low voltage {DK}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Conseq, U	Electricity, low voltage {DK}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Conseq, U	Electricity, low voltage {DK}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Conseq, U & solar collector system, Cu flat plate collector, one-family house, for combined system {{DK}} | Conseq, U - jlm	Electricity, low voltage {DK}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Conseq, U

Ecoinvent processes have been chosen instead of processes already modelled for the project, as these might have zero fuel input (or efficiency) and hence not emit anything, which would be misleading.

Ambient heat

Based on the process “Heat production, at heat pump 30kW, allocation exergy Europe without Switzerland” a process for heat pump has been made, excluding the electricity input that ecoinvent has, because electricity is accounted for elsewhere in our model. This leaves the infrastructure and an emission to air.

Biodiesel

No processes are available for burning of biodiesel and therefore a process with diesel is taken as a proxy and the fuel input is modified from conventional diesel to biodiesel, assuming the same LHV and same technology. For households and Commercials: The chosen process is the smaller, a process of 10MW is also available.

Biogas

The process is an edited version of "Electricity, low voltage {CH}| biogas, burned in micro gas turbine 100kWe | Conseq, U", where the negative heat input has been removed, and all inputs and emissions have been scaled to the amount of methane used (which afterwards was deleted), in order to get impacts from burning biogas. The chosen starting process is the only one with gas turbine.

Biomass

For households and commercial biomass is assumed to be wood pellets burned for heating. Wood stoves also fall in this category, but no process is available in ecoinvent for this. For wood pellets various capacities are available: According to (Energinet.dk and Danish Energy Agency 2018) for single houses it is 8-12 kW, and for apartment complexes it is 160-400kW. Ecoinvent has processes of 9, 15, 25 and 300kW. (50kW is an obsolete process.) Both 9kW and 300kW are included and assigned half of the energy demand each.

Original ecoinvent processes "Heat, central or small-scale, other than natural gas {CH}| heat production, wood pellet, at furnace 9kW | Conseq, U" and "Heat, central or small-scale, other than natural gas {CH}| heat production, wood pellet, at furnace 300kW | Conseq, U" have been modified to use country specific low voltage mix rather than the ecoinvent mix.

For agriculture, the 300kW process has been chosen.

Geothermal

Many processes exist for various countries; however, they all have the same inputs, i.e. anyone is as good as the other, and therefore the process for Austria was chosen at random.

Solar

It is assumed that sectors agriculture, commercial and industry only use PV solar cells, whereas households use a mix of PV and thermal. No ratio is given, so an even split of half of each is assumed. For thermal a combined system process "Heat, central or small-scale, other than natural gas {CH}| operation, solar collector system, Cu flat plate collector, one-family house, for combined system | Conseq, U", is used as starting point, where the electricity input has been changed to the country specific low voltage mix of our model.

Waste

The incineration of waste is modelled as the ecoinvent waste process "Municipal solid waste {DK}| treatment of, incineration | Conseq, U", where the input of electricity and heat are negative, and modify this to an energy process, where the former (negative) energy inputs are the new (positive) outputs. The amount of waste is left out, because the model inputs the energy in the waste rather than the mass. This process is used in all four sectors. (In the Base Pathway only Industry has an actual use of energy from waste, but for the sake of completeness it is included in all four sectors.)

Others

In the output tables from TIMES this is explained as “Methanol, Hydrogen, DME”. No combustion processes for these fuels exist on their own in ecoinvent; as a starting point the emissions from cars combusting the fuels have been used as a proxy for the emissions from this. (The numbers are very small in the Base Pathway for all four sectors.)

Stoves

For sectors Household and Commercial some energy is used for cooking. This has been modelled separately for electricity, natural gas, oil, solar and biomass (wood). The process for the stove and for emissions from burning natural gas has been taken from the supplementary information of Frischknecht et al. (2016). For electricity and solar no emissions have been included, just the infrastructure, for oil and wood the same emissions have been used as a proxy and due to lack of better data. Net calorific values for natural gas and diesel have been taken from (IEA 2017) or coal stove ecoinvent had the process listed in the table.

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Appendix C – Environmental impact assessment results

Table C1. Total impact assessment results for the Base Pathway in 2015-2050

					Impact score				
Impact category	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Climate change (ReCiPe)	*kg CO2 eq.*	6.2E+12	5.6E+12	5.8E+12	5.7E+12	5.4E+12	5.2E+12	4.7E+12	4.2E+12
Climate change, HH (ReCiPe)	*DALY*	5.8E+06	5.2E+06	5.3E+06	5.3E+06	5.0E+06	4.8E+06	4.4E+06	3.9E+06
Water scarcity index (Pfister)	*m3*	2.3E+10	2.5E+10	2.8E+10	3.3E+10	3.7E+10	4.1E+10	4.3E+10	3.5E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	4.5E+03	4.2E+03	3.5E+03	3.8E+03	3.8E+03	4.0E+03	4.4E+03	4.5E+03
Ionizing radiation (ReCiPe)	*DALY*	9.0E+03	8.4E+03	5.3E+03	3.9E+03	2.3E+03	3.1E+03	3.7E+03	4.3E+03
Ozone formation, HH (ReCiPe)	*DALY*	1.3E+04	1.2E+04	1.2E+04	1.2E+04	1.2E+04	1.2E+04	1.2E+04	1.1E+04
Particulate matter (ReCiPe)	*DALY*	8.7E+06	8.0E+06	7.6E+06	7.2E+06	6.5E+06	6.2E+06	5.8E+06	5.3E+06
Human carc. toxicity (ReCiPe)	*DALY*	1.0E+06	9.4E+05	1.0E+06	1.0E+06	9.5E+05	8.9E+05	8.3E+05	7.8E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	1.7E+06	1.7E+06	2.4E+06	2.5E+06	2.2E+06	1.9E+06	2.0E+06	1.9E+06
Land use (ReCiPe)	*species.yr*	2.7E+03	2.7E+03	2.7E+03	2.7E+03	2.7E+03	2.9E+03	2.8E+03	2.4E+03
Damages to human health (ReCiPe)	*DALY*	3.4E-02	3.4E-02	3.1E-02	3.2E-02	3.2E-02	3.6E-02	3.1E-02	3.5E-02
Human toxicity, cancer (USEtox)	*cases*	4.3E+05	4.0E+05	4.3E+05	4.2E+05	4.0E+05	3.7E+05	3.4E+05	3.2E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.2E+17	1.1E+17	1.0E+17	1.1E+17	1.0E+17	1.0E+17	1.1E+17	1.1E+17

Table C2. Total impact assessment results for the Paris Agreement Pathway in 2015-2050

		Impact score							
Impact category	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Climate change (ReCiPe)	*kg CO2 eq.*	6.2E+12	5.7E+12	5.7E+12	5.6E+12	4.5E+12	4.0E+12	3.4E+12	3.2E+12
Climate change, HH (ReCiPe)	*DALY*	5.8E+06	5.3E+06	5.3E+06	5.2E+06	4.2E+06	3.7E+06	3.2E+06	3.0E+06
Water scarcity index (Pfister)	*m3*	2.3E+10	2.5E+10	2.8E+10	3.2E+10	4.1E+10	4.5E+10	4.7E+10	5.1E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	4.5E+03	4.3E+03	3.5E+03	3.8E+03	4.1E+03	3.8E+03	3.8E+03	3.9E+03
Ionizing radiation (ReCiPe)	*DALY*	9.0E+03	8.5E+03	5.3E+03	3.8E+03	2.3E+03	3.2E+03	4.0E+03	5.3E+03
Ozone formation, HH (ReCiPe)	*DALY*	1.3E+04	1.3E+04	1.2E+04	1.2E+04	1.2E+04	1.1E+04	1.1E+04	1.0E+04
Particulate matter (ReCiPe)	*DALY*	8.7E+06	8.1E+06	7.9E+06	7.6E+06	5.9E+06	5.3E+06	5.1E+06	5.2E+06
Human carc. toxicity (ReCiPe)	*DALY*	1.0E+06	9.7E+05	1.1E+06	1.1E+06	8.4E+05	8.2E+05	8.6E+05	9.6E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	1.7E+06	1.7E+06	3.5E+06	3.6E+06	1.9E+06	1.9E+06	2.3E+06	2.8E+06
Land use (ReCiPe)	*species.yr*	2.7E+03	2.8E+03	2.7E+03	2.6E+03	2.8E+03	4.2E+03	5.5E+03	6.0E+03
Damages to human health (ReCiPe)	*DALY*	3.4E-02	3.2E-02	3.6E-02	3.5E-02	2.6E-02	2.4E-02	2.3E-02	2.4E-02
Human toxicity, cancer (USEtox)	*cases*	4.3E+05	4.1E+05	4.8E+05	4.9E+05	3.5E+05	3.4E+05	3.6E+05	4.0E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.2E+17	1.1E+17	1.1E+17	1.2E+17	1.0E+17	9.8E+16	1.0E+17	1.1E+17

Table C3. Impact assessment results for the Base Pathway in 2015 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.64E+11	9.16E+11	1.66E+12	1.37E+12	2.12E+12
Climate change, HH (ReCiPe)	*DALY*	1.52E+05	8.50E+05	1.54E+06	1.27E+06	1.97E+06
Water scarcity index (Pfister)	*m3*	4.73E+08	4.31E+09	6.89E+09	6.88E+09	4.43E+09
Stratospheric ozone depletion (ReCiPe)	*DALY*	6.53E+01	1.03E+03	1.76E+03	1.03E+03	6.08E+02
Ionizing radiation (ReCiPe)	*DALY*	1.05E+02	2.88E+03	4.51E+03	1.33E+03	1.91E+02
Ozone formation, HH (ReCiPe)	*DALY*	6.18E+02	1.22E+03	2.21E+03	3.49E+03	5.79E+03
Particulate matter (ReCiPe)	*DALY*	2.23E+05	9.98E+05	1.79E+06	1.77E+06	3.93E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.76E+04	1.69E+05	2.84E+05	1.70E+05	3.66E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	8.34E+04	3.13E+05	5.32E+05	3.64E+05	4.46E+05
Land use (ReCiPe)	*species.yr*	1.51E+02	2.12E+02	8.80E+02	3.34E+02	1.08E+03
Damages to human health (ReCiPe)	*DALY*	9.63E-04	4.65E-03	8.25E-03	7.11E-03	1.33E-02
Human toxicity, cancer (USEtox)	*cases*	1.15E+04	7.14E+04	1.20E+05	7.64E+04	1.53E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.84E+15	2.82E+16	4.71E+16	2.71E+16	1.40E+16

Table C4. Impact assessment results for the Paris Agreement Pathway in 2015 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.62E+11	8.98E+11	1.67E+12	1.36E+12	2.12E+12
Climate change, HH (ReCiPe)	*DALY*	1.50E+05	8.33E+05	1.55E+06	1.26E+06	1.96E+06
Water scarcity index (Pfister)	*m3*	4.62E+08	4.28E+09	6.99E+09	6.87E+09	4.42E+09
Stratospheric ozone depletion (ReCiPe)	*DALY*	6.33E+01	1.02E+03	1.79E+03	1.03E+03	6.07E+02
Ionizing radiation (ReCiPe)	*DALY*	9.78E+01	2.85E+03	4.55E+03	1.30E+03	1.90E+02
Ozone formation, HH (ReCiPe)	*DALY*	6.17E+02	1.22E+03	2.26E+03	3.50E+03	5.79E+03
Particulate matter (ReCiPe)	*DALY*	2.21E+05	9.96E+05	1.82E+06	1.77E+06	3.93E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.74E+04	1.68E+05	2.88E+05	1.70E+05	3.65E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	8.33E+04	3.12E+05	5.41E+05	3.63E+05	4.43E+05
Land use (ReCiPe)	*species.yr*	1.51E+02	2.12E+02	9.12E+02	3.34E+02	1.08E+03
Damages to human health (ReCiPe)	*DALY*	9.57E-04	4.60E-03	8.36E-03	7.09E-03	1.33E-02
Human toxicity, cancer (USEtox)	*cases*	1.14E+04	7.11E+04	1.21E+05	7.61E+04	1.53E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.80E+15	2.81E+16	4.78E+16	2.70E+16	1.40E+16

Table C5. Impact assessment results for the Base Pathway in 2020 differentiated by sector

Impact category	**Unit**	**Agriculture**	**Commercial**	**Households**	**Industrial**	**Transport**
Climate change (ReCiPe)	*kg CO2 eq*	1.60E+11	6.50E+11	1.45E+12	1.26E+12	2.11E+12
Climate change, HH (ReCiPe)	*DALY*	1.49E+05	6.03E+05	1.34E+06	1.17E+06	1.96E+06
Water scarcity index (Pfister)	*m3*	7.33E+08	3.69E+09	7.72E+09	7.23E+09	5.28E+09
Stratospheric ozone depletion (ReCiPe)	*DALY*	6.79E+01	7.68E+02	1.73E+03	1.00E+03	6.59E+02
Ionizing radiation (ReCiPe)	*DALY*	9.70E+01	2.17E+03	4.77E+03	1.15E+03	2.56E+02
Ozone formation, HH (ReCiPe)	*DALY*	6.16E+02	8.65E+02	1.89E+03	3.20E+03	5.85E+03
Particulate matter (ReCiPe)	*DALY*	2.16E+05	6.80E+05	1.56E+06	1.62E+06	3.91E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.69E+04	1.20E+05	2.72E+05	1.55E+05	3.69E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	8.34E+04	2.34E+05	5.36E+05	3.63E+05	4.99E+05
Land use (ReCiPe)	*species.yr*	1.65E+02	2.22E+02	8.82E+02	3.57E+02	1.11E+03
Damages to human health (ReCiPe)	*DALY*	9.38E-04	3.25E-03	7.35E-03	6.55E-03	1.33E-02
Human toxicity, cancer (USEtox)	*cases*	1.12E+04	5.08E+04	1.14E+05	6.94E+04	1.54E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.73E+15	2.07E+16	4.67E+16	2.64E+16	1.47E+16

Table C6. Impact assessment results for the Paris Agreement Pathway in 2020 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.66E+11	6.55E+11	1.48E+12	1.26E+12	2.11E+12
Climate change, HH (ReCiPe)	*DALY*	1.54E+05	6.08E+05	1.37E+06	1.17E+06	1.96E+06
Water scarcity index (Pfister)	*m3*	8.08E+08	3.74E+09	7.71E+09	7.24E+09	5.16E+09
Stratospheric ozone depletion (ReCiPe)	*DALY*	6.89E+01	7.91E+02	1.77E+03	9.99E+02	6.34E+02
Ionizing radiation (ReCiPe)	*DALY*	8.97E+01	2.23E+03	4.84E+03	1.13E+03	1.88E+02
Ozone formation, HH (ReCiPe)	*DALY*	6.48E+02	9.11E+02	1.99E+03	3.24E+03	5.87E+03
Particulate matter (ReCiPe)	*DALY*	2.25E+05	7.14E+05	1.62E+06	1.64E+06	3.89E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.81E+04	1.28E+05	2.85E+05	1.58E+05	3.66E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	8.77E+04	2.46E+05	5.55E+05	3.65E+05	4.89E+05
Land use (ReCiPe)	*species.yr*	1.66E+02	2.31E+02	9.15E+02	3.63E+02	1.10E+03
Damages to human health (ReCiPe)	*DALY*	9.85E-04	3.39E-03	7.66E-03	6.64E-03	1.33E-02
Human toxicity, cancer (USEtox)	*cases*	1.17E+04	5.41E+04	1.20E+05	7.06E+04	1.53E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.74E+15	2.15E+16	4.80E+16	2.64E+16	1.41E+16

Table C7. Impact assessment results for the Base Pathway in 2025 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.85E+11	6.24E+11	1.61E+12	1.22E+12	2.12E+12
Climate change, HH (ReCiPe)	*DALY*	1.72E+05	5.80E+05	1.49E+06	1.13E+06	1.97E+06
Water scarcity index (Pfister)	*m3*	1.62E+09	3.26E+09	8.43E+09	6.64E+09	7.85E+09
Stratospheric ozone depletion (ReCiPe)	*DALY*	8.68E+01	5.28E+02	1.42E+03	7.69E+02	7.25E+02
Ionizing radiation (ReCiPe)	*DALY*	5.88E+01	1.17E+03	3.22E+03	5.07E+02	3.17E+02
Ozone formation, HH (ReCiPe)	*DALY*	6.98E+02	7.25E+02	1.80E+03	2.89E+03	6.10E+03
Particulate matter (ReCiPe)	*DALY*	2.39E+05	5.79E+05	1.63E+06	1.51E+06	3.67E+06
Human carc. toxicity (ReCiPe)	*DALY*	3.07E+04	1.12E+05	3.19E+05	1.39E+05	4.09E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	1.01E+05	3.26E+05	9.99E+05	3.33E+05	6.56E+05
Land use (ReCiPe)	*species.yr*	1.83E+02	1.88E+02	8.07E+02	3.16E+02	1.17E+03
Damages to human health (ReCiPe)	*DALY*	1.08E-03	3.16E-03	8.76E-03	6.14E-03	1.32E-02
Human toxicity, cancer (USEtox)	*cases*	1.28E+04	4.74E+04	1.35E+05	6.23E+04	1.71E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.82E+15	1.61E+16	4.52E+16	2.10E+16	1.73E+16

Table C8. Impact assessment results for the Paris Agreement Pathway in 2025 differentiated by sector

Impact category	**Unit**	**Agriculture**	**Commercial**	**Households**	**Industrial**	**Transport**
Climate change (ReCiPe)	*kg CO2 eq*	1.91E+11	6.40E+11	1.65E+12	1.22E+12	2.03E+12
Climate change, HH (ReCiPe)	*DALY*	1.77E+05	5.94E+05	1.53E+06	1.13E+06	1.89E+06
Water scarcity index (Pfister)	*m3*	1.75E+09	3.65E+09	9.36E+09	6.49E+09	6.90E+09
Stratospheric ozone depletion (ReCiPe)	*DALY*	8.87E+01	5.48E+02	1.43E+03	7.73E+02	6.32E+02
Ionizing radiation (ReCiPe)	*DALY*	5.19E+01	1.25E+03	3.35E+03	5.27E+02	1.67E+02
Ozone formation, HH (ReCiPe)	*DALY*	7.36E+02	7.24E+02	1.77E+03	2.86E+03	5.96E+03
Particulate matter (ReCiPe)	*DALY*	2.53E+05	7.16E+05	2.04E+06	1.48E+06	3.46E+06
Human carc. toxicity (ReCiPe)	*DALY*	3.27E+04	1.44E+05	4.18E+05	1.39E+05	3.99E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	1.14E+05	5.89E+05	1.83E+06	3.63E+05	6.21E+05
Land use (ReCiPe)	*species.yr*	1.93E+02	1.99E+02	8.44E+02	3.07E+02	1.11E+03
Damages to human health (ReCiPe)	*DALY*	1.15E-03	4.07E-03	1.16E-02	6.20E-03	1.26E-02
Human toxicity, cancer (USEtox)	*cases*	1.37E+04	6.15E+04	1.78E+05	6.23E+04	1.67E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.90E+15	1.95E+16	5.49E+16	2.13E+16	1.58E+16

Table C9. Impact assessment results for the Base Pathway in 2030 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.84E+11	6.40E+11	1.57E+12	1.16E+12	2.11E+12
Climate change, HH (ReCiPe)	*DALY*	1.71E+05	5.94E+05	1.46E+06	1.08E+06	1.96E+06
Water scarcity index (Pfister)	*m3*	1.92E+09	3.57E+09	8.98E+09	7.05E+09	1.13E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	9.26E+01	6.03E+02	1.50E+03	7.95E+02	8.21E+02
Ionizing radiation (ReCiPe)	*DALY*	3.11E+01	8.78E+02	2.34E+03	2.71E+02	3.47E+02
Ozone formation, HH (ReCiPe)	*DALY*	7.04E+02	7.05E+02	1.65E+03	2.90E+03	6.28E+03
Particulate matter (ReCiPe)	*DALY*	2.36E+05	5.84E+05	1.54E+06	1.40E+06	3.43E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.99E+04	1.10E+05	2.97E+05	1.25E+05	4.42E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	1.00E+05	3.27E+05	9.54E+05	3.25E+05	7.85E+05
Land use (ReCiPe)	*species.yr*	1.94E+02	1.79E+02	6.95E+02	3.39E+02	1.26E+03
Damages to human health (ReCiPe)	*DALY*	1.07E-03	3.19E-03	8.40E-03	5.78E-03	1.30E-02
Human toxicity, cancer (USEtox)	*cases*	1.25E+04	4.63E+04	1.25E+05	5.57E+04	1.85E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.72E+15	1.76E+16	4.63E+16	2.09E+16	2.01E+16

Table C10. Impact assessment results for the Paris Agreement Pathway in 2030 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.77E+11	6.59E+11	1.57E+12	1.15E+12	2.00E+12
Climate change, HH (ReCiPe)	*DALY*	1.64E+05	6.11E+05	1.46E+06	1.07E+06	1.86E+06
Water scarcity index (Pfister)	*m3*	1.81E+09	4.18E+09	1.02E+10	6.64E+09	9.65E+09
Stratospheric ozone depletion (ReCiPe)	*DALY*	8.94E+01	6.59E+02	1.57E+03	7.94E+02	6.76E+02
Ionizing radiation (ReCiPe)	*DALY*	2.92E+01	9.44E+02	2.38E+03	2.58E+02	1.51E+02
Ozone formation, HH (ReCiPe)	*DALY*	6.80E+02	7.53E+02	1.69E+03	2.83E+03	6.16E+03
Particulate matter (ReCiPe)	*DALY*	2.33E+05	7.70E+05	2.02E+06	1.39E+06	3.19E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.98E+04	1.53E+05	4.11E+05	1.27E+05	4.25E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	1.04E+05	6.22E+05	1.80E+06	3.43E+05	7.23E+05
Land use (ReCiPe)	*species.yr*	1.98E+02	1.91E+02	7.07E+02	3.06E+02	1.17E+03
Damages to human health (ReCiPe)	*DALY*	1.06E-03	4.30E-03	1.13E-02	5.84E-03	1.23E-02
Human toxicity, cancer (USEtox)	*cases*	1.25E+04	6.49E+04	1.74E+05	5.65E+04	1.78E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.77E+15	2.24E+16	5.79E+16	2.12E+16	1.72E+16

Table C11. Impact assessment results for the Base Pathway in 2035 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.77E+11	5.81E+11	1.47E+12	1.11E+12	2.04E+12
Climate change, HH (ReCiPe)	*DALY*	1.64E+05	5.39E+05	1.37E+06	1.03E+06	1.90E+06
Water scarcity index (Pfister)	*m3*	2.06E+09	3.83E+09	1.03E+10	7.68E+09	1.36E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	9.30E+01	5.76E+02	1.47E+03	8.38E+02	8.59E+02
Ionizing radiation (ReCiPe)	*DALY*	1.38E+01	4.93E+02	1.41E+03	1.34E+02	2.85E+02
Ozone formation, HH (ReCiPe)	*DALY*	6.82E+02	6.29E+02	1.50E+03	2.93E+03	6.26E+03
Particulate matter (ReCiPe)	*DALY*	2.26E+05	4.99E+05	1.34E+06	1.36E+06	3.11E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.84E+04	9.31E+04	2.59E+05	1.19E+05	4.52E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	9.45E+04	2.49E+05	7.39E+05	3.17E+05	8.35E+05
Land use (ReCiPe)	*species.yr*	1.96E+02	1.72E+02	6.40E+02	3.66E+02	1.28E+03
Damages to human health (ReCiPe)	*DALY*	1.02E-03	2.74E-03	7.36E-03	5.58E-03	1.25E-02
Human toxicity, cancer (USEtox)	*cases*	1.18E+04	3.90E+04	1.08E+05	5.29E+04	1.89E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.60E+15	1.60E+16	4.31E+16	2.13E+16	2.15E+16

Table C12. Impact assessment results for the Paris Agreement Pathway in 2035 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.61E+11	4.00E+11	1.00E+12	1.01E+12	1.97E+12
Climate change, HH (ReCiPe)	*DALY*	1.50E+05	3.71E+05	9.29E+05	9.38E+05	1.83E+06
Water scarcity index (Pfister)	*m3*	1.94E+09	5.46E+09	1.46E+10	7.55E+09	1.15E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	9.01E+01	6.71E+02	1.71E+03	8.78E+02	7.16E+02
Ionizing radiation (ReCiPe)	*DALY*	1.33E+01	5.31E+02	1.49E+03	1.58E+02	1.40E+02
Ozone formation, HH (ReCiPe)	*DALY*	6.39E+02	5.83E+02	1.37E+03	2.78E+03	6.22E+03
Particulate matter (ReCiPe)	*DALY*	2.11E+05	4.52E+05	1.16E+06	1.12E+06	2.92E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.59E+04	7.55E+04	2.00E+05	9.92E+04	4.38E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	8.65E+04	1.91E+05	5.17E+05	2.94E+05	7.89E+05
Land use (ReCiPe)	*species.yr*	2.00E+02	2.23E+02	7.61E+02	3.59E+02	1.22E+03
Damages to human health (ReCiPe)	*DALY*	9.51E-04	2.21E-03	5.70E-03	4.91E-03	1.19E-02
Human toxicity, cancer (USEtox)	*cases*	1.08E+04	3.07E+04	8.04E+04	4.38E+04	1.84E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.53E+15	1.72E+16	4.49E+16	2.15E+16	1.82E+16

Table C13. Impact assessment results for the Base Pathway in 2040 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.73E+11	5.35E+11	1.40E+12	1.12E+12	2.00E+12
Climate change, HH (ReCiPe)	*DALY*	1.60E+05	4.97E+05	1.30E+06	1.04E+06	1.85E+06
Water scarcity index (Pfister)	*m3*	2.22E+09	3.61E+09	1.01E+10	1.07E+10	1.45E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	9.53E+01	5.57E+02	1.50E+03	1.01E+03	8.70E+02
Ionizing radiation (ReCiPe)	*DALY*	1.61E+01	6.13E+02	1.85E+03	2.61E+02	3.57E+02
Ozone formation, HH (ReCiPe)	*DALY*	6.68E+02	5.51E+02	1.32E+03	3.64E+03	6.20E+03
Particulate matter (ReCiPe)	*DALY*	2.18E+05	4.22E+05	1.14E+06	1.47E+06	2.92E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.72E+04	7.62E+04	2.15E+05	1.25E+05	4.44E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	9.01E+04	1.68E+05	4.77E+05	3.68E+05	8.29E+05
Land use (ReCiPe)	*species.yr*	2.03E+02	1.92E+02	6.35E+02	5.75E+02	1.29E+03
Damages to human health (ReCiPe)	*DALY*	9.94E-04	2.32E-03	6.27E-03	5.98E-03	1.20E-02
Human toxicity, cancer (USEtox)	*cases*	1.13E+04	3.15E+04	8.82E+04	5.56E+04	1.86E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.50E+15	1.47E+16	4.07E+16	2.47E+16	2.17E+16

Table C14. Impact assessment results for the Paris Agreement Pathway in 2040 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.28E+11	2.89E+11	7.24E+11	8.96E+11	1.96E+12
Climate change, HH (ReCiPe)	*DALY*	1.19E+05	2.69E+05	6.72E+05	8.31E+05	1.82E+06
Water scarcity index (Pfister)	*m3*	1.75E+09	5.66E+09	1.61E+10	9.44E+09	1.22E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	8.52E+01	5.84E+02	1.58E+03	8.64E+02	7.40E+02
Ionizing radiation (ReCiPe)	*DALY*	3.51E+01	6.63E+02	1.98E+03	3.56E+02	1.77E+02
Ozone formation, HH (ReCiPe)	*DALY*	4.96E+02	5.13E+02	1.24E+03	2.91E+03	6.30E+03
Particulate matter (ReCiPe)	*DALY*	1.68E+05	3.82E+05	1.03E+06	1.04E+06	2.72E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.10E+04	6.73E+04	1.89E+05	9.38E+04	4.46E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	6.98E+04	1.81E+05	5.28E+05	3.00E+05	8.46E+05
Land use (ReCiPe)	*species.yr*	1.96E+02	5.02E+02	1.58E+03	6.60E+02	1.26E+03
Damages to human health (ReCiPe)	*DALY*	7.63E-04	1.84E-03	4.96E-03	4.56E-03	1.16E-02
Human toxicity, cancer (USEtox)	*cases*	8.72E+03	2.72E+04	7.56E+04	4.12E+04	1.87E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.49E+15	1.50E+16	4.17E+16	2.07E+16	1.94E+16

Table C15. Impact assessment results for the Base Pathway in 2045 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.45E+11	4.33E+11	1.17E+12	1.04E+12	1.90E+12
Climate change, HH (ReCiPe)	*DALY*	1.35E+05	4.03E+05	1.09E+06	9.67E+05	1.77E+06
Water scarcity index (Pfister)	*m3*	1.90E+09	3.59E+09	1.06E+10	1.25E+10	1.40E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	8.42E+01	5.99E+02	1.67E+03	1.21E+03	8.59E+02
Ionizing radiation (ReCiPe)	*DALY*	1.88E+01	6.78E+02	2.16E+03	4.46E+02	4.12E+02
Ozone formation, HH (ReCiPe)	*DALY*	5.63E+02	4.42E+02	1.04E+03	3.93E+03	6.03E+03
Particulate matter (ReCiPe)	*DALY*	1.86E+05	3.87E+05	1.08E+06	1.41E+06	2.72E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.26E+04	6.44E+04	1.88E+05	1.20E+05	4.33E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	7.59E+04	1.61E+05	4.72E+05	4.03E+05	8.48E+05
Land use (ReCiPe)	*species.yr*	1.93E+02	1.59E+02	5.45E+02	6.74E+02	1.24E+03
Damages to human health (ReCiPe)	*DALY*	8.45E-04	2.05E-03	5.70E-03	5.84E-03	1.15E-02
Human toxicity, cancer (USEtox)	*cases*	9.42E+03	2.60E+04	7.50E+04	5.25E+04	1.81E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.31E+15	1.54E+16	4.42E+16	2.87E+16	2.21E+16

Table C16. Impact assessment results for the Paris Agreement Pathway in 2045 differentiated by sector

Impact category	**Unit**	**Agriculture**	**Commercial**	**Households**	**Industrial**	**Transport**
Climate change (ReCiPe)	*kg CO2 eq*	8.22E+10	2.26E+11	5.37E+11	7.24E+11	1.85E+12
Climate change, HH (ReCiPe)	*DALY*	7.63E+04	2.10E+05	4.98E+05	6.72E+05	1.72E+06
Water scarcity index (Pfister)	*m3*	1.26E+09	6.34E+09	1.71E+10	9.65E+09	1.24E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	6.99E+01	5.86E+02	1.54E+03	8.13E+02	7.65E+02
Ionizing radiation (ReCiPe)	*DALY*	5.79E+01	7.78E+02	2.19E+03	5.50E+02	3.96E+02
Ozone formation, HH (ReCiPe)	*DALY*	2.97E+02	5.10E+02	1.19E+03	2.48E+03	6.27E+03
Particulate matter (ReCiPe)	*DALY*	1.11E+05	4.05E+05	1.08E+06	9.25E+05	2.59E+06
Human carc. toxicity (ReCiPe)	*DALY*	1.47E+04	7.82E+04	2.17E+05	9.25E+04	4.63E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	4.96E+04	2.45E+05	7.16E+05	2.91E+05	9.51E+05
Land use (ReCiPe)	*species.yr*	1.74E+02	7.73E+02	2.25E+03	8.94E+02	1.40E+03
Damages to human health (ReCiPe)	*DALY*	5.08E-04	1.92E-03	5.16E-03	4.00E-03	1.14E-02
Human toxicity, cancer (USEtox)	*cases*	6.08E+03	3.17E+04	8.73E+04	4.03E+04	1.93E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.41E+15	1.58E+16	4.29E+16	1.94E+16	2.30E+16

Table C17. Impact assessment results for the Base Pathway in 2050 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	7.39E+10	3.81E+11	1.06E+12	8.88E+11	1.82E+12
Climate change, HH (ReCiPe)	*DALY*	6.86E+04	3.54E+05	9.86E+05	8.24E+05	1.69E+06
Water scarcity index (Pfister)	*m3*	6.59E+08	2.43E+09	7.33E+09	1.14E+10	1.29E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	6.32E+01	6.24E+02	1.68E+03	1.27E+03	8.29E+02
Ionizing radiation (ReCiPe)	*DALY*	6.38E+01	6.91E+02	2.30E+03	7.22E+02	4.86E+02
Ozone formation, HH (ReCiPe)	*DALY*	2.13E+02	3.88E+02	8.81E+02	3.46E+03	5.82E+03
Particulate matter (ReCiPe)	*DALY*	8.89E+04	3.82E+05	1.03E+06	1.28E+06	2.55E+06
Human carc. toxicity (ReCiPe)	*DALY*	1.07E+04	5.89E+04	1.72E+05	1.13E+05	4.25E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	3.39E+04	1.57E+05	4.61E+05	3.94E+05	8.75E+05
Land use (ReCiPe)	*species.yr*	1.37E+02	1.10E+02	3.57E+02	6.09E+02	1.16E+03
Damages to human health (ReCiPe)	*DALY*	4.09E-04	1.92E-03	5.36E-03	5.30E-03	1.12E-02
Human toxicity, cancer (USEtox)	*cases*	4.38E+03	2.35E+04	6.75E+04	4.88E+04	1.77E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.34E+15	1.60E+16	4.46E+16	3.01E+16	2.26E+16

Table C18. Impact assessment results for the Paris Agreement Pathway in 2050 differentiated by sector

Impact category	Unit	Agriculture	Commercial	Households	Industrial	Transport
Climate change (ReCiPe)	*kg CO2 eq*	1.23E+11	2.70E+11	4.65E+11	5.67E+11	1.79E+12
Climate change, HH (ReCiPe)	*DALY*	1.14E+05	2.51E+05	4.31E+05	5.26E+05	1.66E+06
Water scarcity index (Pfister)	*m3*	2.40E+09	1.08E+10	1.72E+10	8.36E+09	1.20E+10
Stratospheric ozone depletion (ReCiPe)	*DALY*	9.94E+01	8.49E+02	1.52E+03	7.15E+02	7.37E+02
Ionizing radiation (ReCiPe)	*DALY*	5.46E+01	1.54E+03	2.45E+03	7.78E+02	4.50E+02
Ozone formation, HH (ReCiPe)	*DALY*	5.25E+02	6.98E+02	1.11E+03	1.74E+03	6.18E+03
Particulate matter (ReCiPe)	*DALY*	1.79E+05	6.53E+05	1.16E+06	7.73E+05	2.47E+06
Human carc. toxicity (ReCiPe)	*DALY*	2.39E+04	1.41E+05	2.45E+05	8.84E+04	4.63E+05
Human non-carc. toxicity (ReCiPe)	*DALY*	8.38E+04	5.27E+05	9.15E+05	2.63E+05	1.01E+06
Land use (ReCiPe)	*species.yr*	2.12E+02	1.34E+03	2.19E+03	8.60E+02	1.38E+03
Damages to human health (ReCiPe)	*DALY*	8.13E-04	3.23E-03	5.62E-03	3.34E-03	1.12E-02
Human toxicity, cancer (USEtox)	*cases*	9.96E+03	5.70E+04	9.95E+04	3.81E+04	1.94E+05
Freshwater ecotoxicity (USEtox)	*PAF.m3.day*	1.71E+15	2.54E+16	4.51E+16	1.75E+16	2.36E+16

Appendix D – Material demand intensity

In this Appendix we detail our assumptions on the level of material demand intensity, that is associated with each representative technology, and provide our sources where relevant. We assume that the intensities are generally static, but that they do take into account the TIMES Pan-EU assumptions on how battery pack sizes change across time.

Lighting

Transition lighting technologies considered in this report include energy efficient fluorescent lamps and lamps based on light emitting diode (LED) technology, both of which are explicitly considered in the TIMES-PanEU model as replacements for conventional incandescent lighting. In the case of fluorescent lighting, we have assumed an even split between compact fluorescent lighting (CFL) and linear fluorescent lamps (LFC). Per-unit data on material demand is sourced from work by Grandell et al. [17].

Table D1. Material Intensity Assumptions for Lighting

Material	Fluorescent Lighting (g/lamp)	LED Lighting (g/lamp)
Europium (Eu)	0.085	-
Gallium (Ga)	-	0.53
Indium (In)	-	0.00017
Lanthanum (La)	0.21	-
Terbium (Tb)	0.085	-
Yttrium (Y)	0.93	0.45

Electric Vehicles

Transition vehicle technologies explicitly included in this report are covered below, along with assumptions about their battery capacity size and electric motor size (in the case of hybrids we focus on the electric motor rather than the alternative powertrain). In the case of battery electric vehicles and plug-in hybrid, the model assumes in most cases that capacity increases significantly over time, and this is reflected also in our material assessment. Battery pack sizes for hybrid electric and fuel cell vehicles do not change through time in the TIMES-PanEU model version used for this assessment.

Table D2. Vehicle Technologies Overview

Vehicle Type	Body Style	Drivetrain Type	Electric Motor Size (kW)	Battery Size 2010 (kWh)	Battery Size 2050 (kWh)
Passenger cars	Small	Battery Electric	37-55	18	30
		Hybrid Electric		0.5	0.5
		Plug-in Hybrid		10	10
		Fuel Cell Hybrid		10	10
		Fuel Cell		0	0
Passenger cars	Medium	Battery Electric	120-180	30	75
		Hybrid Electric		1.5	1.5

		Plug-in Hybrid		12	12
		Fuel Cell Hybrid		12	12
		Fuel Cell		0	0
Passenger cars	Large	Battery Electric	300	74	150
		Hybrid Electric		2.5	2.5
		Plug-in Hybrid		19	19
		Fuel Cell Hybrid		19	19
		Fuel Cell		0	0
Buses		Battery Electric	147-220	540	1080
		Hybrid Electric		2	2
		Plug-in Hybrid		117	154
		Fuel Cell Hybrid		1.8	1.8
		Fuel Cell		0	0
Light duty vehicles (LDVs)		Battery Electric	77-115	30	60
		Hybrid Electric		1	1
		Plug-in Hybrid		24	31
		Fuel Cell Hybrid		1	1
		Fuel Cell		0	0
Heavy duty vehicles (HDVs)		Hybrid Electric	220-330	3	3
		Plug-in Hybrid		107	151
		Fuel Cell Hybrid		2.7	2.7
		Fuel Cell		0	0
Motorcycles		Battery Electric	20	10	10

Per-unit data on material demand for different drivetrains are sourced from Moss et al. 2013 [13] and scaled to the different representative vehicle types. This then gives an estimate of total material demand for each representative vehicle, as shown below for passenger cars, buses, LDVs, HDVs, and motorcycles. Leading battery chemistries for the future of the European electromobility market appear to be nickel cobalt aluminium (NCA) and nickel cobalt manganese (NCM), with no clear trends at the time of writing regarding whether one of these will dominate in the coming decades. We have therefore assumed an even split between these battery chemistries in our assessment.

Table D3. Material Intensity Assumptions for Passenger Cars – Battery Electric

Material	**Passenger Cars – Battery Electric (kg/vehicle)**					
	Small		**Medium**		**Large**	
	2010	**2050**	**2010**	**2050**	**2010**	**2050**
Cobalt (Co)	5.75	11.18	9.58	23.95	23.63	47.89
Dysprosium (Dy)	0.22	0.22	0.72	0.72	1.20	1.20
Lanthanum (La)	-	-	-	-	-	-
Lithium (Li)	2.80	5.44	4.66	11.65	11.49	23.29
Neodymium (Nd)	2.20	2.20	7.20	7.20	12.00	12.00
Praseodymium (Pr)	-	-	-	-	-	-

Table D4. Material Intensity Assumptions for Passenger Cars – Other Drivetrains

Material	**Passenger Cars – Hybrid Electric (kg/vehicle)**	**Passenger Cars – Plug-in Hybrid (kg/vehicle)**	**Passenger Cars – Fuel Cell Hybrid (kg/vehicle)**	**Passenger Cars – Fuel Cell (kg/vehicle)**

	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
Cobalt (Co)	0.12	0.35	0.59	2.33	2.80	4.43	2.35	2.82	4.46	-	-	-
Dysprosium (Dy)	0.43	1.39	3.48	0.30	0.99	1.65	0.26	0.86	1.43	0.26	0.86	1.43
Lanthanum (La)	1.72	5.57	13.92	-	-	-	-	-	-	-	-	-
Lithium (Li)	0.17	0.17	0.29	1.13	1.35	2.14	1.15	1.38	2.19	-	-	-
Neodymium (Nd)	1.66	5.38	13.44	2.01	6.57	10.95	1.78	5.82	9.70	1.78	5.82	9.70
Praseodymium (Pr)	0.12	0.38	0.96	-	-	-	-	-	-	-	-	-

Table D5. Material Intensity Assumptions for Buses

Material	Bus – Battery Electric (kg/vehicle)		Bus – Hybrid Electric (kg/vehicle)	Bus – Plug-in Hybrid (kg/vehicle)		Bus – Fuel Cell Hybrid (kg/vehicle)	Bus – Fuel Cell (kg/vehicle)
	2010	2050		2010	2050		
Cobalt (Co)	172.40	344.81	0.43	27.25	35.97	0.43	-
Dysprosium (Dy)	0.88	0.88	1.71	1.21	1.21	1.05	1.05
Lanthanum (La)	-	-	6.82	-	-	-	-
Lithium (Li)	83.85	167.70	0.21	13.20	17.42	0.21	-
Neodymium (Nd)	8.80	8.80	6.59	8.03	1.21	7.11	7.11
Praseodymium (Pr)	-	-	0.47	-	-	-	-

Table D6. Material Intensity Assumptions for Light Duty Vehicles (LDVs)

Material	LDV – Battery Electric (kg/vehicle)		LDV – Hybrid Electric (kg/vehicle)	LDV – Plug-in Hybrid (kg/vehicle)		LDV – Fuel Cell Hybrid (kg/vehicle)	LDV – Fuel Cell (kg/vehicle)
	2010	2050		2010	2050		
Cobalt (Co)	9.58	19.16	0.22	5.52	7.28	0.22	-
Dysprosium (Dy)	0.46	0.46	0.89	0.63	0.63	0.55	0.55
Lanthanum (La)	-	-	3.57	-	-	-	-
Lithium (Li)	4.66	9.32	0.11	2.67	3.53	0.11	-
Neodymium (Nd)	4.60	4.60	3.45	4.20	4.20	3.72	3.72
Praseodymium (Pr)	-	-	0.25	-	-	-	-

Table D7. Material Intensity Assumptions for Heavy Duty Vehicles (HDVs)

Material	HDV – Hybrid Electric (kg/vehicle)	HDV – Plug-in Hybrid (kg/vehicle)		HDV – Fuel Cell Hybrid (kg/vehicle)	HDV – Fuel Cell (kg/vehicle)
		2010	2050		
Cobalt (Co)	0.64	24.90	32.86	0.64	-
Dysprosium (Dy)	2.55	1.82	1.82	1.58	1.58
Lanthanum (La)	10.21	-	-	-	-
Lithium (Li)	0.31	12.06	15.92	0.32	-
Neodymium (Nd)	9.86	12.05	12.05	10.67	10.67
Praseodymium (Pr)	0.70	-	-	-	-

Table D8. Material Intensity Assumptions for Motorcycles

Material	Motorcycle – Battery Electric (kg/vehicle)
Cobalt (Co)	3.19
Dysprosium (Dy)	0.08
Lanthanum (La)	-
Lithium (Li)	1.55
Neodymium (Nd)	0.80
Praseodymium (Pr)	-

Power Generation Technologies

The material requirements for power generation technologies assumed in this report are based on Moss et al. 2011 [23]. For nuclear power, the assumptions imply that the reactor deployments across the modelled time horizon represent either Westinghouse AP1000 or Areva EPR designs. For solar photovoltaics, a mixture of crystalline silicon (80%), amorphous silicon (10%) and thin film technologies (5% CdTe and 5% CIGS) is assumed. For wind power, our assumptions imply that most European wind turbines are using electromagnet generators, with the share of permanent magnets increasing slightly over time. Permanent magnet technology starts at 15% of market share and rises to 20% by 2020.

Table D9. Material Intensity Assumptions for Power Generation

Material	Nuclear Power (kg/MW)	Solar Photovoltaic Power (kg/MW)	Wind Power (kg/MW)
Dysprosium (Dy)	-	-	2.8
Gallium (Ga)	-	0.12	-
Hafnium (Hf)	0.48	-	-
Indium (In)	1.6	4.5	-
Neodymium (Nd)	-	-	40.6
Tellurium (Te)	-	4.7	-
Yttrium (Y)	0.5	-	-

Fuel Cells

The materials requirements for fuel cells assumed in this report are based on Moss et al. 2013 [13].

Table D10. Material Intensity Assumptions for Fuel Cells

Material	Fuel Cells (kg/MW)
Cobalt (Co)	10.8
Lanthanum (La)	38.0
Platinum (Pt)	67.9
Yttrium (Y)	8.4

Electricity Storage Batteries

The materials requirements for electricity storage assumed in this report are based on a range of sources. A brief review of grid-scale electricity storage systems from leading manufacturers such as LG Chem, Samsung and Panasonic at the time of writing reveals that they typically comprise packaged units (i.e. containerised) with 1-5 MWh of energy each. These individual units are then purchased in volume and assembled into modular grid storage schemes. Data on large-scale lithium battery systems for grid storage applications (10 MW> capacity) from the United States Department of Energy's Energy Storage database[3] suggests that these schemes are highly heterogeneous and range in size from 10-120 MWh and are designed to operate at full discharge for anything from between 1-4 hours. The data also show an increasing trend towards larger capacity schemes that are designed to operate for longer time periods.

In real world deployment grid storage schemes will be subjected to constraints such as financing, land availability, and the technical contribution required to the network. For this study we have assumed that a "typical" scheme as we move forward into the period 2020 – 2050 in Europe could be 10 – 100 MWh in size and designed to discharge at full capacity for 4 hours (i.e. 10 – 25 MW peak capacity). We also have assumed that nickel cobalt manganese (NCM) will be the dominant battery chemistry for electricity storage batteries as this appears to be used at the time of writing by the broadest range of manufacturers.

Table D11. Material Intensity Assumptions for Electricity Storage Batteries

Material	Electricity Storage Battery (kg/MW)
Cobalt (Co)	840
Lithium (Li)	640

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[3] Available online at: https://www.energystorageexchange.org/